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FINAL REPORT
9438 HIGH LEVEL TRAVELING WAVE TUBE AMPLIFIER ANOMALY

VOLUME I

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Report No. 28600-AR-015-01

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11 August 1978

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Los Angeles Air Force Station
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Los Angeles, Calif. 90009

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This technical report has been reviewed and is approved for publication.

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The results of an investigation into orbit failures of HLTWTA on DSCS-II satellite are presented along with recommendation for corrections on future TWTAs to be issued on DSCS-II. The possible causes of these failures are examined in light of orbit data, and laboratory simulation testing.

REPORT SAMSO-TR-77-184

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9438 HIGH LEVEL TRAVELING WAVE TUBE AMPLIFIER ANOMALY

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PREFACE

This report presents the 9438 High-Level Traveling Wave Tube Amplifier (HLTWTA) anomaly investigation with conclusions and recommendations. The investigation also reviewed past DSCS-II TWTA failures and findings in an attempt to obtain a better understanding of possible failure modes and their likelihood with this type of amplifier. The 9438 satellite is still in operation using the redundant HLTWTA and is providing all desired communications service. It was not possible to state the exact cause of the 9438 failure, but considerable insights were gained during these investigations regarding potential failures and problem areas in this type of TWTA designed for space application. Many of the recommendations arising from these investigations are being implemented on TWTAs scheduled for use on future DSCS-II satellites. Hence, it can be anticipated that future DSCS-II satellites will experience less of this type of failure.

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1. INTRODUCTION

1. INTRODUCTION

On 20 May 1977, 6 days after launch, a Narrow-Coverage High-Level Traveling Wave Tube Amplifier (NCHLTWTA-1) on Satellite 9438 shut off without warning or receiving ground commands. Several attempts to restart it failed. The redundant HLTWTA was commanded ON sucessfully. This occurrence represented the third failure of a HLTWTA in orbit on DSCS-II satellites. In addition, a similar failure of this type of TWTA had already occurred on another program's satellite. Finally, a fourth DSCS-II HLTWTA failure occurred on Satellite 9434 several days later, making a total of five orbit failures of this type of TWTA. An intensive investigation was undertaken to seek a common cause and identify corrective action to reduce the risk of additional TWTA failures in DSCS-II satellites.

This report summarizes the findings of a team of TRW and Hughes Aircraft Corporation engineering and system effectiveness personnel assembled after the failure to address the questions posed above.

1.1 CHARACTERIZATION OF DSCS-II TWTA ORBIT FAILURES

The four DSCS-II HLTWTA orbit failures to date have had one common factor: they all happened without warning, and were all absolute (i.e., no additional useful operation could be obtained from the failed amplifier after initial failure). Before the failure, all telemetry data appeared nominal, and the performance of the communications subsystem and HLTWTA were proper. Afterward, the amplifier could not be restarted and did not produce useful or measurable power output.

Three of the four DSCS-II failures exhibited another common characteristic which became apparent when attempts were made to restart the failed unit. Upon receipt of a ground command, the TWTA power supply turns on and applies power to the TWT heater for nominally 90 seconds before the high voltages are applied. In the case of three of the four DSCS-II failures, the heater turn-on and high-voltage delay timing operated satisfactorily. It was upon application of high voltages that the TWTA shut itself off. This shutdown occurred rapidly between samples of TWTA input current which is measured every 1.024 seconds. The fourth DSCS-II failure differed in that there was no response to the TWTA turn-on commands at all. No

input current was drawn and no heater voltage was generated. There are a number of failure modes which can produce this type of phenomenon which would not produce the one seen on the three earlier failures. However, there are also other failure modes which can produce both types of characteristics.

1.2 CAUSES OF ANOMALOUS PERFORMANCE

To assess the cause of the multiple amplifier failures, a variety of test, analysis, and simulation activities were performed. It was not possible to deduce a single failure mode for each failure; rather, conclusions could only be reached which described a probable cause of all failures. It was also possible to conclude with high confidence that certain types of failure did not occur.

Conclusions regarding cause of failure reached by these investigations are:

- The anomaly is not due to a failure in the satellite electrical systems which support the HLTWTA; for example, electrical power, command, and telemetry.
- The failures were not induced by malfunctions of the interfacing RF components.
- The most likely failure mechanism is a high-voltage breakdown in either the traveling wave tube (TWT) collector assembly or the TWT power supply high-voltage module.
- For the Flight 8 (F8) failure only, it is equally possible that the unit was launched with a latent defect in the high-voltage module not totally resolved during module testing.

The third conclusion can be further refined in that ground testing and hardware examinations performed on units of the same lot scheduled for subsequent satellites showed a preference for TWT collector assembly failures over power supply high-voltage module failures.

Another possible, but less likely, failure mechanism cannot be completely ruled out. This would be a change in the operating point of the helix overcurrent trip circuit in the TWTA power supply. However, if this were an actual common cause of the orbit failures, some evidence of drift or malfunction should have appeared during ground testing. No such evidence could be found to support this candidate.

In addition to conclusions directly related to orbit failures, certain conclusions concern design and testing of TWTAs used on DSCS-II:

- Thermal vacuum testing of DSCS-II HLTWTAs prior to launch is insufficient.

- The TWT collector assembly potting system is not well understood and is a weak aspect of TWTA design.

The relationship between these two sets of conclusions, coupled with the need to complete subsequent DSCS-II satellites on time, constitutes a driving force which helped shape the corrective action recommendations arising from this investigation.

The quality and process control techniques and practices involved in the manufacture of the HLTWTA were reviewed as part of the anomaly team investigation. Basically, the quality control was satisfactory. However, it is felt that improvements can be made, particulary in the area of the TWT encapsulation process.

1.3 RELATIONSHIP TO HLTWTA ANOMALIES OF OTHER PROGRAMS

As noted above, the HLTWTA used on DSCS-II is also used on one other space communication satellite. The design of the power supply in the amplifiers used on the other satellite differs from DSCS-II in that the helix overcurrent trip circuit is disabled at launch. Thus, it is not possible for a TWTA to shut itself off in orbit due to excess helix current. The input overcurrent trip circuit is operative so that a TWTA can shut itself off if it senses the input current is excessive.

The satellite power distribution system is different from DSCS-II in that a resettable circuit breaker is used for primary fault isolation rather than fuses.

The TWTA failure on this satellite exhibited one characteristic not seen on the DSCS-II failures. Specifically, the TWTA could be restarted and operated successfully for a short period after it shut down. This was done afer the first two shutdowns. After the third, the restart attempt was unsuccessful.

Although it is not the purpose of this investigation to definitively state the cause of this failure, it is possible to sketch a scenario which relates it to the DSCS-II failures. With the helix overcurrent trip cir-

cuit disabled, the TWTA could be slightly less sensitive to automatic shut down during restarting when short high-voltage discharges have occurred. Thus, it could be possible to restart a TWTA several times before the high-voltage breakdown path becomes low enough in impedance to preclude further operation.

One of the TWTAs on a commercial satellite demonstrated a shutoff, but could be turned on every time. The shutoffs occurred on 25 January 1977, and 10, 11, and 18 March 1977. The power control unit and power supply design of this commercial satellite are different from DSCS-II, but the TWTA and its power supply are manufactured by the same manufacturer.

It is also believed that there are two other shutoff occurrences, either on this same satellite on another of the same series. This involves one or two TWTAs. The failures occurred early in the life of the satellite (approximately within 2 months of flight), and it is believed that the TWTA(s) are now in "OFF" condition.

The difference between these failures and the ones on DSCS-II were not considered sufficiently large by the group studying this anomaly that they could be ignored. Although specific conclusions regarding the probable cause of the DSCS-II failures were not based on these failures, this group did not see any contradictory conclusions evolving from these failures.

1.4 TWTA DESCRIPTION

The high-level traveling wave tube amplifier (HLTWTA) consists of a unit containing the traveling wave tube (TWT) and its power supply. The power supply assembly consists of the chassis, semiconductor module, high-voltage module, filter capacitor module, and other miscellaneous components, wiring, and connectors. The filter capacitor module and other miscellaneous components are bonded in place. The semiconductor module is held in the chassis by 13 screws and thermal bonding at the bottom and back surfaces of the module. The high-voltage module is held in place by bonding the base surface and affixing a sheet metal clamp with screws which restrains any movement of the encapsulant. The unit is hard wired, with all wires spot bonded in place as required for vibration protection. Select-in-test components are installed at this assembly.

1.4.1 Mechanical Construction, Power Supply

The semiconductor module consists of a heat sink or substructure and three multilayer PC boards. The boards are mechanically assembled to top and bottom sheet metal flanges to form an "L" beam structure. The stud-mounted semiconductors are bonded to channels fastened between the flanges. The module is hard wired, tested and inspected, conformal coated, and encapsulated with foam. Gold sheet 0.005-inch thick is bonded on the outside of the finished module. The outside layers of the PC boards are completely redundant 1-ounce copper circuitry. The inner layer of 2-ounce copper is for heat transfer and chassis ground. Total board thickness is 0.060 inch. The boards have a fused solder plated finish, plated through holes, edge plating for heat transfer, and terminals for select-in-test resistors and external connections. Heat transfer pads are located under all transistors.

The high-voltage module consists of all the high-voltage components: transformers, capacitors, chokes, diode bridges, and other miscellaneous parts which are bonded to a fiberglass base and to each other with specific clearances for dielectric insulation. Heat transfer is accomplished through copper and beryllium spacers. The unit is hard wired following specific wire routing and clearance instructions. The diode bridge sub-assemblies are gold wrapped. The finished unit is tested, inspected, and vacuum encapsulated with PRC 1535. Module output is through terminals and insulated flying leads. The telemetry board is physically attached and part of this module.

The filter capacitors on the high-level unit are foam encapsulated into a module of 12 capacitors. The low-level unit has four capacitors chassis-mounted on standoffs, and eight capacitors mounted on a two-sided PC board bonded to the chassis. The entire TWTA assembly is mounted in a deep brazed aluminum chassis measuring 12 inches long, 5 inches wide and 3.06 inches high. Access to the assembly is through a top cover approximately the same size as the top of the TWTA.

1.4.2 Electrical Design, Power Supply

The power supply is a switching regulator, followed by a high-voltage dc/dc converter. A functional block diagram of each TWTA is shown in Figure 1.4-1.

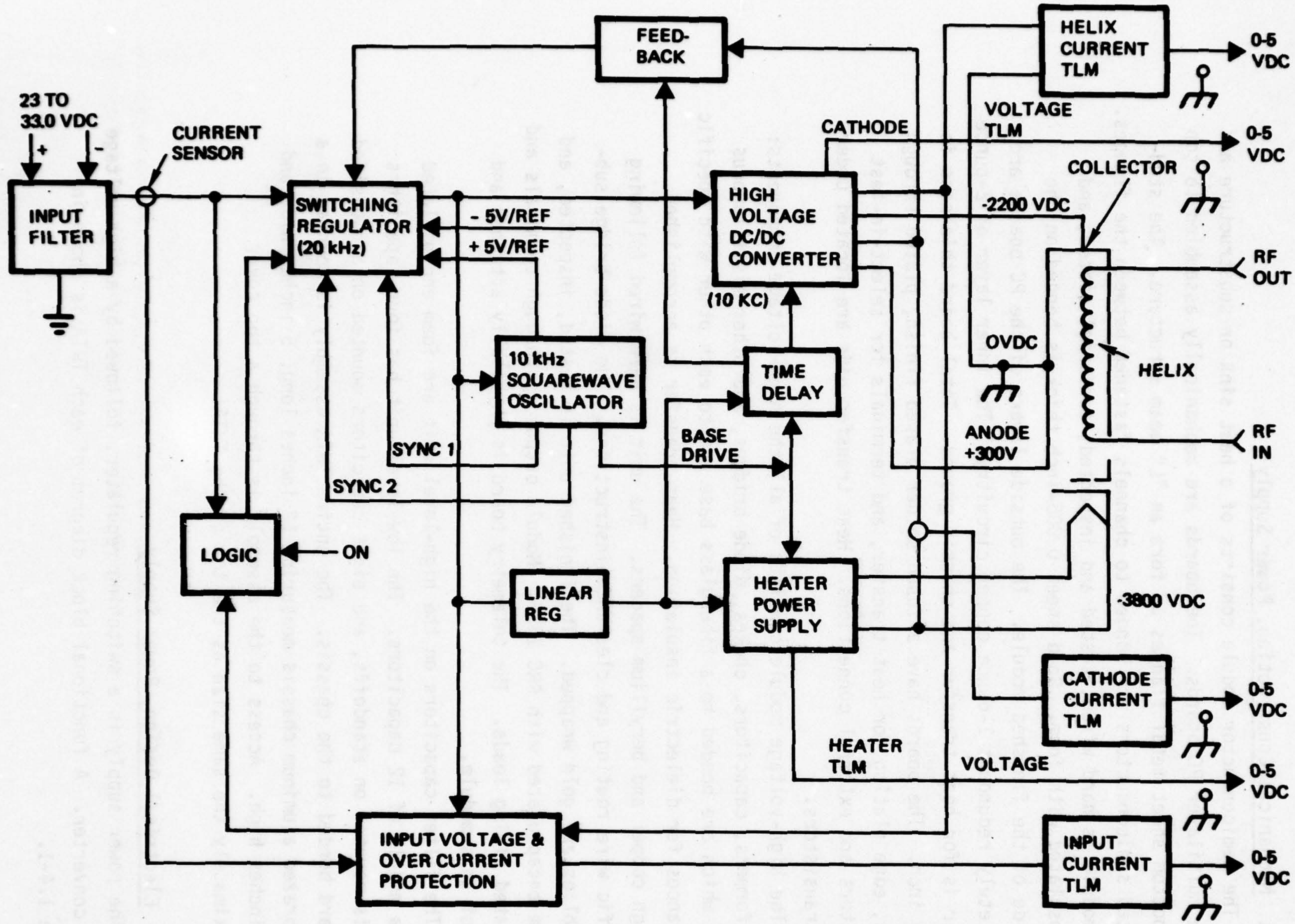

FIGURE 1.4-1. FUNCTIONAL BLOCK DIAGRAM OF TWTA POWER SUPPLY

The input filter is an "L" filter whose low cutoff frequency is about 1 kHz. The input filter also presents 250 μFd (equivalent at) the input bus at 100 Hz.

a) It must decide whether an overcurrent condition exists.

b) It must provide temporary base current to the power switch for turn-on.

c) It must turn the supply on and off according to the presence or absence of the ON command and protective circuit inputs.

If the helix current should rise too high, the helix protection circuit would activate and turn the supply off. The current is calibrated such that 5 to 7 mA of helix current causes power supply shutdown due to helix current overload. A low-pass filter removes any high-frequency signal from the helix current overload input. The input current overload signal is summed with the helix current overload signal at the input of the overload comparator.

After a delay, the comparator will begin to conduct when an overload exists. This shunts the current from the ON command to ground and in turn causes the power supply to turn off. The ON command must be removed, then reapplied to turn the supply back on.

The switching regulator produces an output voltage of about 19 volts at a power level of over 90 watts. It exhibits an operating efficiency of approximately 90 percent from one-half to full load.

The switching regulator contains several functions within itself. A block diagram of the switching regulator (Figure 1.4-2) includes a power switch, a driver for the switch, an amplifier, a reference voltage, a feedback signal, a low-pass filter (or integrator), and a circuit to convert from analog to pulse width.

The reference voltage is developed across a temperature compensated reference diode, VR1. The feedback signal is developed by a resistive divider from the cathode voltage. The low-pass filter (or integrator) consists of L1 and C13. The conversion from analog to pulse width is accomplished by the comparator in Figure 1.4-2.

Audio susceptibility has dominated certain areas of regulator design. The switching regulator is just as stated, a switch. It is either on or off and does not operate in any linear fashion. During the ON condition,

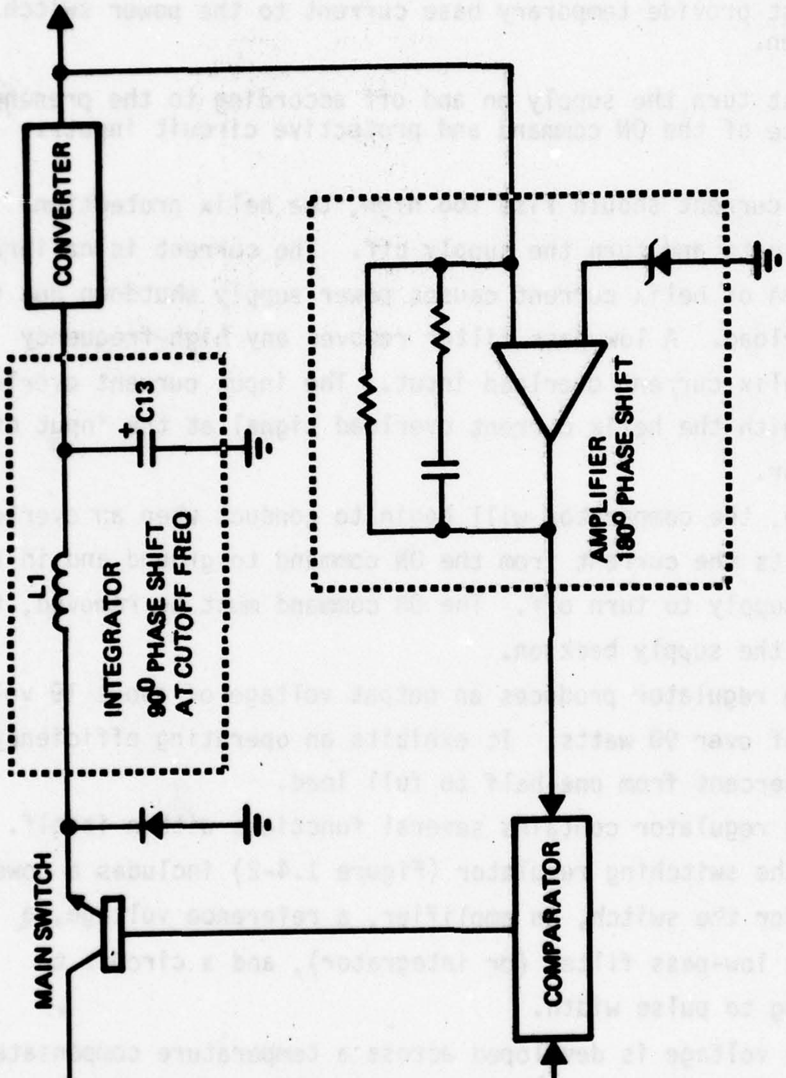

Figure 1.4-2. Power Supply Switching Regulator

the input voltage fed to the switch is the input voltage fed to the integrator (L1 and C13). Refer to Figure 1.4-1. The gain bandwidth of the feedback amplifier is limited to suppress oscillations which will occur in a 360-degree feedback closed loop system with gain. Such a system is the one shown in Figure 1.4-2. The signal applied to the base of the switch transistor goes through 90 degrees of phase shift when processed through the integrator (90-degree phase shift at the integrator cutoff frequency). Soon (small percentage of cutoff frequency) the phase shift reaches 135 degrees, as shown in Figure 1.4-3, and eventually 180 degrees. The feedback amplifier has a phase shift of 180 degrees at the beginning. Thus, it is necessary to keep the total phase shift to less than 270 degrees to have a stability margin for the system. The integrator is designed so that at 20 kHz, the attenuation of the signal from the switch is at least 40 dB. The integrator must therefore have a cutoff frequency of 1800 Hz. At 1800 Hz, there is something near a 90-degree phase shift. The amplifier is designed to have a gain of less than one at 1800 Hz to prevent oscillation. The amplifier has a gain frequency characteristic rolloff of only 20 dB per decade. Thus, the amplifier response starts to decay at the very low frequency of 18 Hz, at a rate of 20 dB/decade, so that at 1800 Hz its gain will be very nearly unity. The very low frequency point for amplifier roll-off beginning creates less gain through the amplifier at the critical audio levels of from 30 to 2000 Hz. Two methods are used to minimize the audio signals which reach the output bus. The first involves the input filter.

The i[illegible]t filter has a low cutoff frequency. The two response curves cros[illegible]frequency that as amplifier gain is lost, attenuation of any audio signals through the input filter increases. Weight and size restrictions limit the cutoff frequency of the input filter to about 1 kilocycle.

A second method used for audio signal attenuation is the introduction of that signal directly into the gain switch loop prior to any phase shift. This is accomplished through the charging circuit surrounding Q20. Through this circuit, the audio signal is injected directly to the comparator ramp signal. An attenuation of a factor of 20 to 50 is achieved in this way.

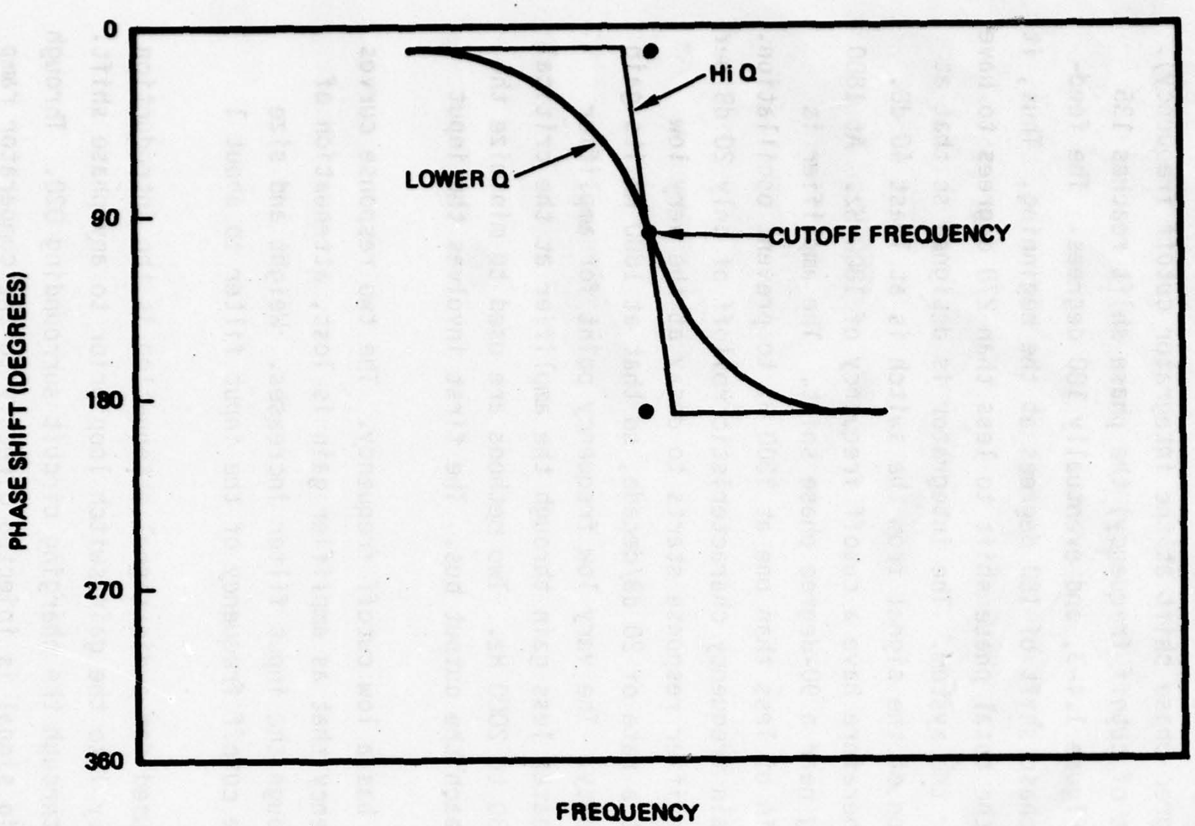

Figure 1.4-3. Phase Shift in Power Supply Integrator

The linear regulator for the 1202H TWTA performs two functions. It supplies a regulated bus voltage for cathode heater power, and it acts in a current limiting capacity during initial turn-on of the system. The need for a second regulated bus to provide cathode heater power stems from the fact that the switching regulator bus may vary as much as 3 percent in maintaining the less than 1 percent regulation required on the cathode helix voltage. This variation, plus variation in the converters, would not allow maintenance of the 3 percent regulation required on the cathode heater voltage.

The time delay circuit inhibits application of high voltage to the TWT until the heater is sufficiently warm to provide proper emission. The duration of the delay is about 90 seconds nominally.

The bias converter is a free-running dc/dc converter which produces these drive voltages for the other two dc/dc converters, synchronization signals for the switching regulator, and ± 5 Vdc bias voltages for the switching regulator. The ± 5 Vdc voltages are "floated" on the switching regulator output voltage.

The bias converter uses a saturable core and separate feedback windings to oscillate at about 10 kilocycles. The large current spikes that are typical of free running converters have been reduced by adding four components.

A capacitor has been added from each base to common, and a resistor included from each emitter to common. Near the end of each half-cycle, when the core saturates, the collector current tries to increase rapidly. This additional current tries to increase the emitter voltage. As it does, the base-to-common capacitor tries to hold the base where it was before core saturation began. This helps remove base current and turn the ON transistor off much faster. As the ON transistor turns off, the OFF transistor is turned on. Coupling capacitors C4 and C6 help the transition to occur quickly and positively.

The converter starts when the bus voltage begins to rise. When the bus voltage rises, current can flow through R1 to the center tap of the feedback winding. This begins to forward bias the bases of Q9 and Q10. One of these transistors will begin to turn on, and will induce a voltage in the feedback winding to reinforce this turn-on action. A similar voltage is induced in the other half of the feedback winding which is phased to turn the OFF transistor harder off. As the bus rises, these feedback voltages reach their normal operating levels and normal oscillation occurs.

Base current returns to the feedback winding center tap through CR5. The starting current through R7 continues to flow while the converter is running.

Most of the power used by the 1202H TWT flows through the high-voltage dc/dc converter. The input voltage is about 19 Vdc and the current is about 4 amperes.

There are two major supplies developed by the high-voltage converter. The helix-to-collector supply is a 2.4 kV supply whose normal load current will be less than 10 mA. A 1.6 kV supply of about 50 mA is "stacked" on top of the collector supply to give a 4.0 kV (maximum) output total. The helix is grounded to the chassis so that cathode potential is a negative 4.0 kV. The anode voltage (about 250 Vdc) is also developed in the high-voltage converter.

The -2.4 kV output is produced by stacking four full wave bridges. Three of the four secondary windings develop about 750 volts and one produces about 300 volts. Four other 400-volt windings drive four more full wave bridges to develop the -1.6 kV collector-to-cathode output. Each set of windings has sufficient taps to adjust depression ratio and set output voltage.

Converter spikes and rectification noise are filtered by a "double L" filter before delivery to the load. Each bridge is isolated from the bridges above or below by a 100 mH choke. This is to help reduce diode stress during the switching interval.

The high-voltage filters use 750 mH chokes and 0.01 μFd capacitors. The collector output filter cuts off at about 1.3 kHz. The cathode filter is about 750 Hz. They offer more than 40 dB attenuation to the 20 kHz square wave input noise. The filters were chosen as inductive input to help minimize inrush currents when high voltage is applied (after time delay). This is important in meeting inrush current limitations.

Three telemetry signals are developed by the high-voltage converter. The helix-to-cathode voltage TLM output is taken from an auxiliary winding on the converter transformer. This winding will produce about 5 Vdc when the cathode voltage is about -4 kV.

Helix current is developed across a resistor of about 1 k ohm. The resistor value is adjusted to give the required voltage for overload during cathode activity test.

Cathode current is measured for telemetry by a saturable reactor or magnetic amplifier. A description of the operation of the saturable core reactor is included later in this section. The reactor is placed in series with the collector-to-cathode supply, and is about -2.4 kV from chassis ground. A 20 volt, 10 kilocycle wave is required to produce the +5 Vdc telemetry output. The 5 volt output will be developed when approximately 60 mA of cathode current is flowing.

The anode supply is a very low current supply with low regulation and ripple requirements. It is taken from a resistive voltage divider. This simplifies transformer design by removing several taps which could otherwise be required.

During heater warm-up, when the time delay circuit is timing out, the high-voltage dc/dc converter is prevented from working. This is done by shunting base drive away from the chopper transistor bases. A detailed description of the operation of this circuit is found later in this section.

The heater power dc/dc converter is a driven converter operating from the linear regulator output and driven at 10 kHz by the bias converter. The heater requires about 5.2 volts at 400 mA for proper emission. This power is delivered at the same potential as the cathode. The ac signal from the transformer is rectified and filtered before delivery to the TWT filament. A full-wave center tap winding is used in the heater transformer and two 3-ampere diodes are used for rectification. A 100 μFd capacitor is used to obtain very low ripple values.

During the time delay period, when the heater is warming up, the linear regulator current limits and prohibits excessive heater currents from flowing. This period represents the maximum power load on the dc/dc converter.

The following telemetry data are required in the form of analog voltages in the range of 0 to 5 Vdc with respect to the chassis of the TWTA:

a) Heater voltage

b) Helix current

c) Cathode-helix voltage

d) Cathode current

e) Input current.

Cathode and input current are monitored and converted to an analog voltage by the saturable reactor form of magnetic amplifier. This method allows conversion from dc current to a dc voltage which is a function of the dc current and the magnetic characteristics of the amplifier or reactor. A calibration curve is drawn which relates actual current flow to output voltage.

Output voltages to be monitored are produced by low voltage windings that give voltages directly proportional to the load voltage. The low-voltage winding produces a 5 volt square wave which is rectified to give a dc voltage proportional to the voltage monitored. A family of telemetry calibration curves, as opposed to a general or single curve, is developed for each of these measurements.

The requirement for increased resolution of the helix voltage required 25 volt winding to be used for the TLM output. A 22 volt Zener diode is used to subtract 22 volts from the original 25 to give about a 3 volt output. Changes in bus voltage (which would produce changes in helix voltage) are reflected by changes in the 25 volt winding. An increase of about a factor of five has resulted in the sensitivity of the helix voltage TLM output.

1.4.3 TWT Description

The high-level TWT (Model 265H) is of PPM-focused lightweight metal ceramic design. A schematic of TWT operation is shown in Figure 1.4-4. Primary design parameters are listed in Table 1.4-1. The TWT comprises three basic assemblies: (1) vacuum assembly, (2) magnet stack, and (3) package.

The vacuum assembly is a conventional helix traveling wave tube with pierce-type convergent-beam electron gun. An oxide-coated cathode is employed in the gun. The drift tube circuit is a triangulated assembly consisting of barrel, baryllia support rods, and helix. Carbon is pyrolytically deposited on the rods to provide sufficient attenuation properly portioned for stability and match requirements. Pipe mounted ceramic windows provide means for introducing and extracting the RF wave. An isolated collector is provided at the output end of the circuit. Figure 1.4-5 shows the basic TWT configuration.

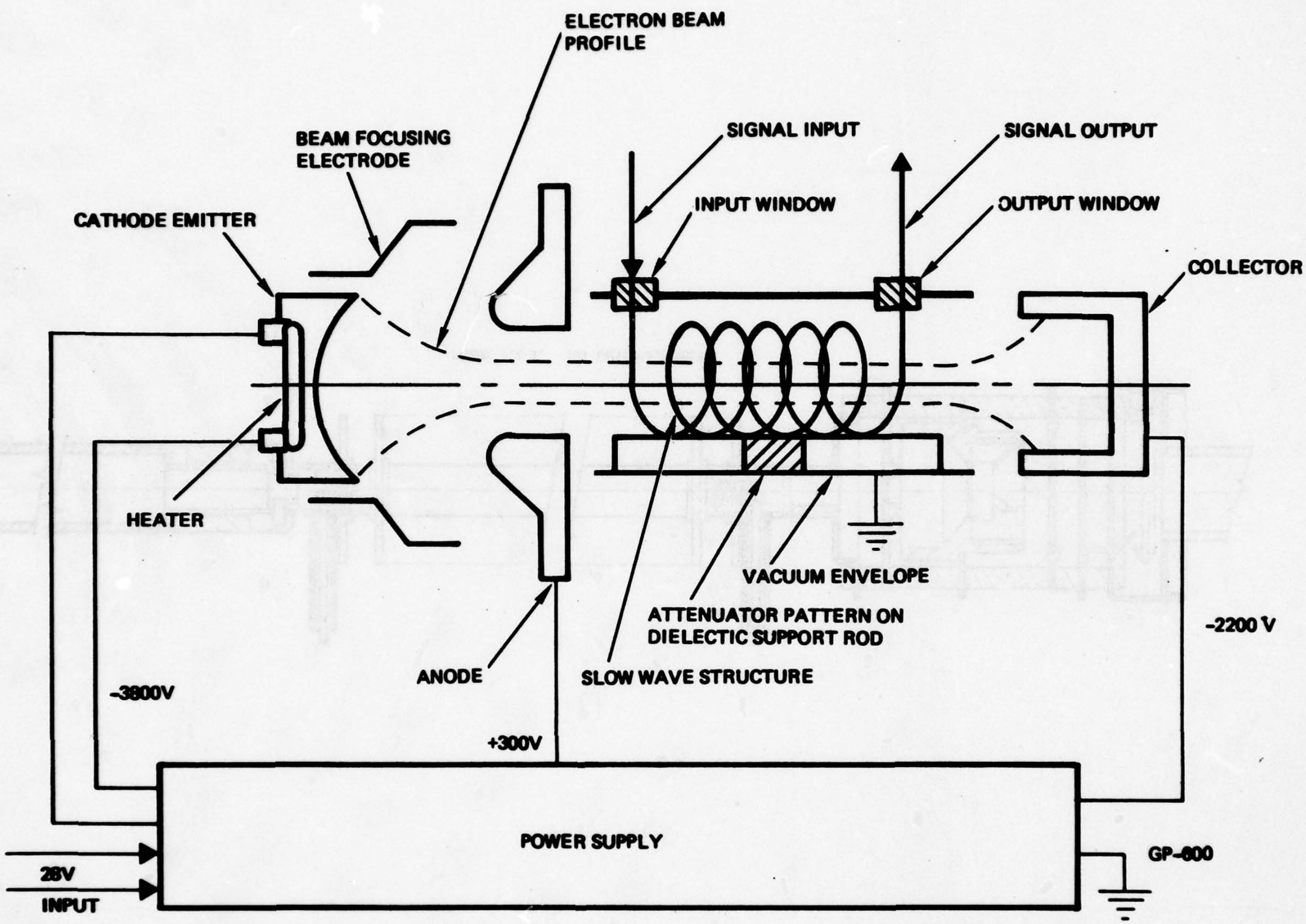

FIGURE 1.4-4. TWT SCHEMATIC DIAGRAM

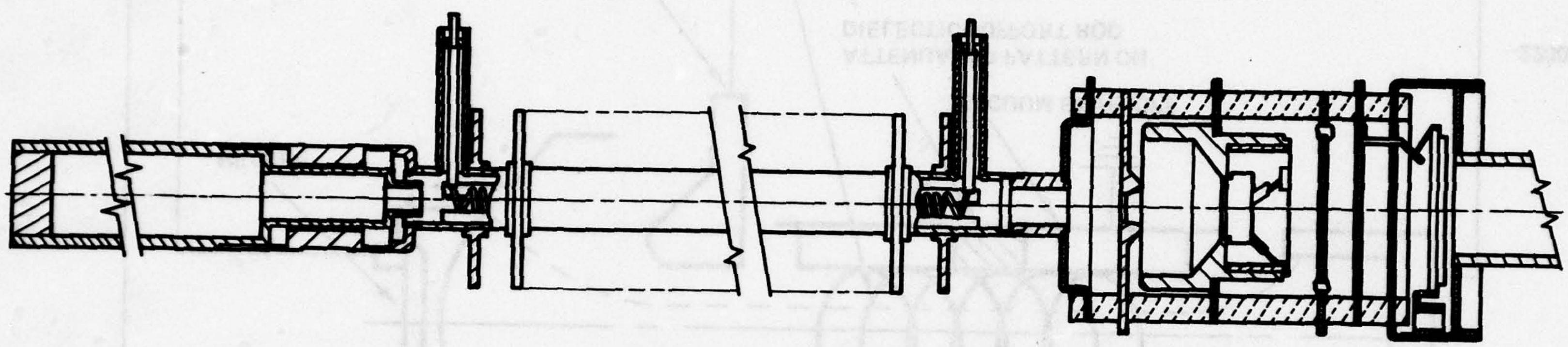

FIGURE 1.4-5. TWT VACUUM ASSEMBLY

Table 1.4-1. Operating Design Parameters 265H TWT

Output power	20.4 watts (minimum)
Frequency band	As specified
Focusing	PPM (platinum cobalt)
Beam voltage	3900 volts
Collector depression	63 percent
Beam perveance	0.21×10^{-6} a/v
Cathode loading	200 mA/cm^2
Beam diameter	0.040 inch
Helix diameter	0.0775 inch
Helix pitch	0.0300 inch
Primary power	79 watts

Platinum-cobalt PPM-configured magnets are employed, together with plated high-purity iron pole pieces, to provide the magnetic field to maintain beam focusing.

The vacuum assembly, with focusing magnets in place, is suspended in polyurethane potting within an aluminum package. Collector support and conductive heat sinking are provided through an electrically isolated heat sink to the mounting surface assembly. Additional heat conduction is provided by loading the potting with alumina. The external package forms a protective envelope for the potted traveling wave tube and provides support for the RF connector adaptors. Figures 1.4-6 and 1.4-7 show the TWT package configuration.

1.5 SYSTEM INTERFACES

The HLTWTA functions as the output power amplifier for each of the two (EC and NC) communications transmitters on the 777 satellite. An identical backup unit is provided for each operating amplifier, making a total of four HLTWTAs on each satellite. The functional location of the HLTWTAs within the 777 transponder is shown in Figure 1.5-1. The major interfaces between the satellite and the TWTAs are command, telemetry, structural, thermal, and primary power.

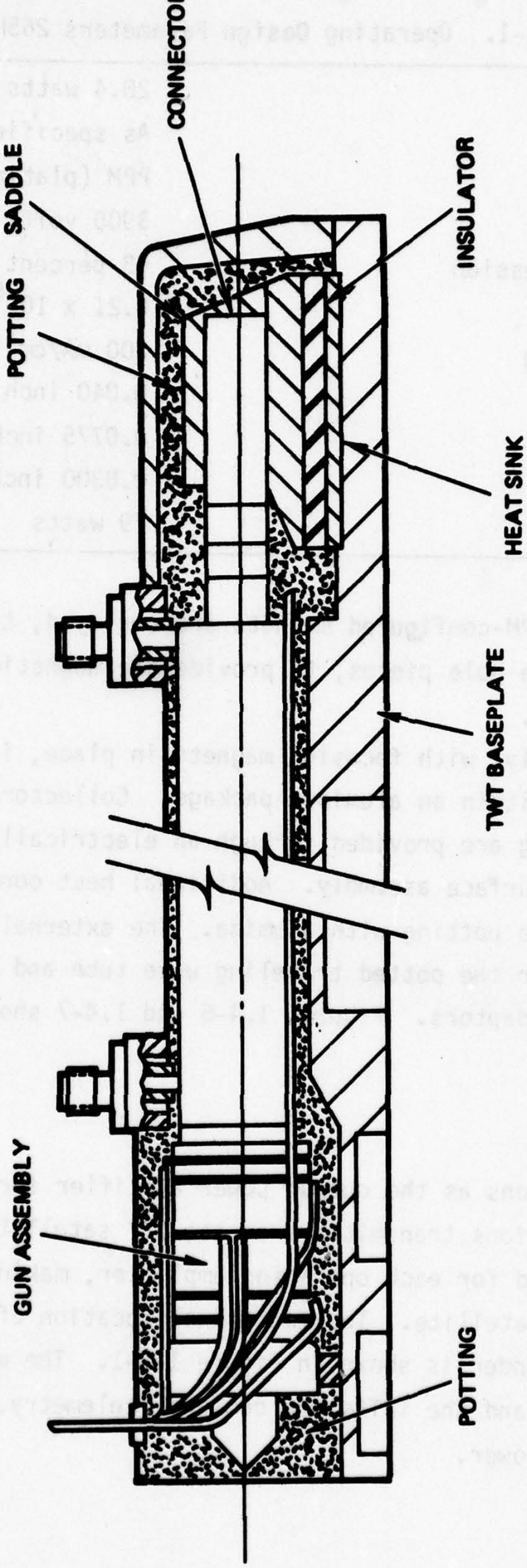

Figure 1.4-6. High Level TWT Package Assembly

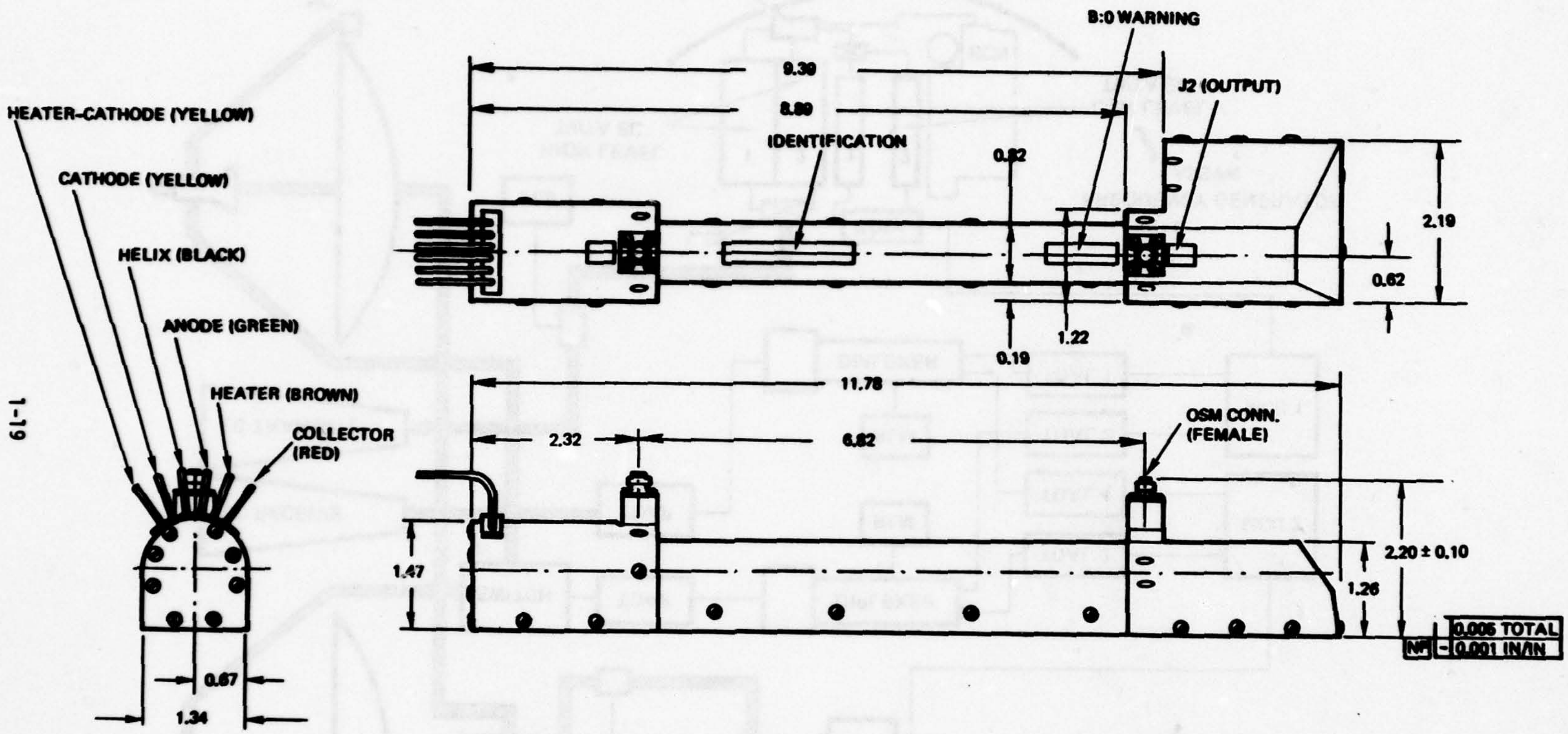

FIGURE 1.4-7. TWTA EXTERNAL CONFIGURATION

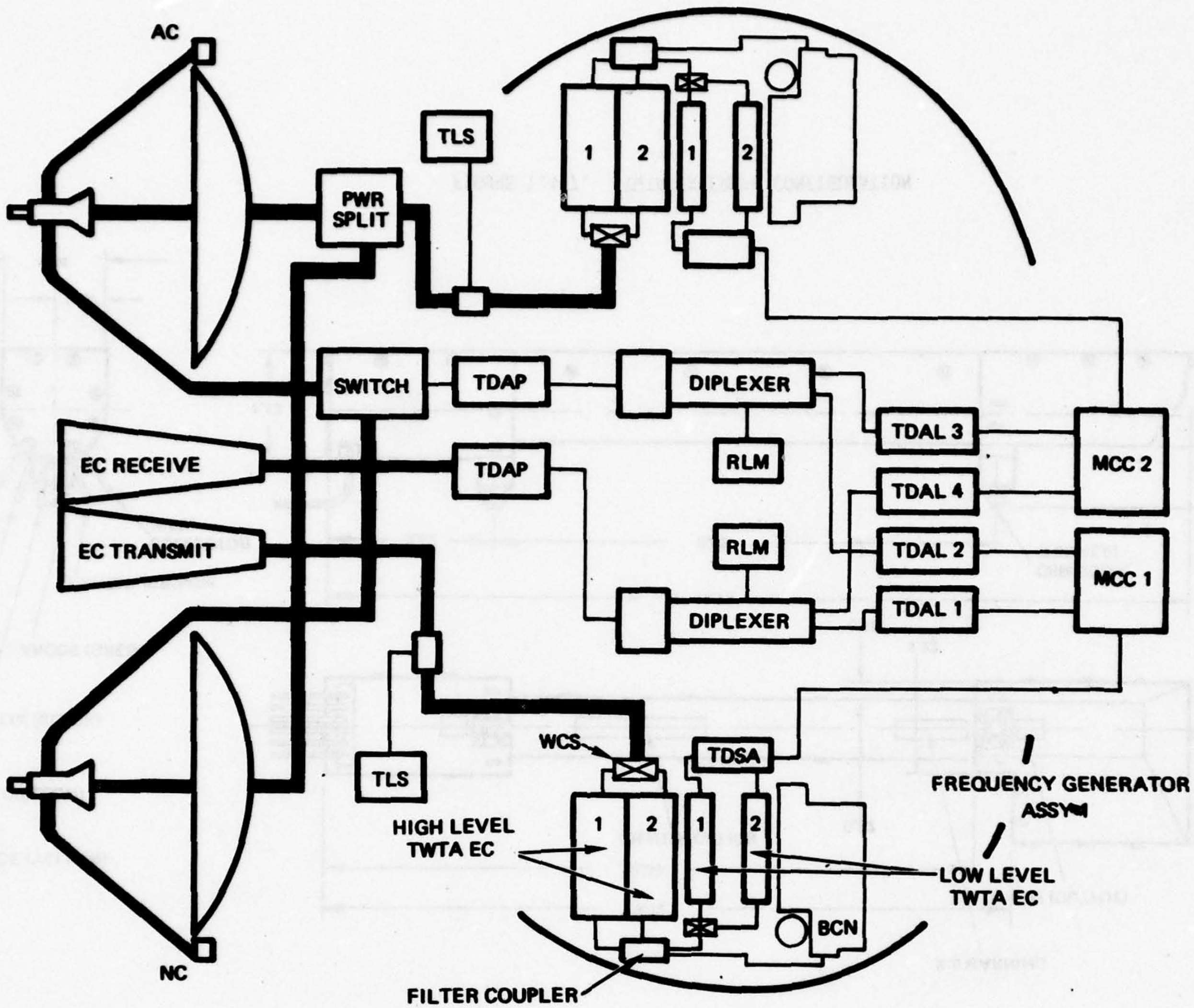

FIGURE 1.5-1. DSCS II TRANSPONDER

1.5.1 Command Interface

The ON command for the HLTWTA is a steady-state +5 Vdc signal supplied by the SLA. As shown in Figure 1.5-2, this signal is supplied from the 5 volt output of the SLA converter through relay contacts in the SLA. Signal return for this ON command is through the TWTA, SLA, and despun platform structure. It should be noted that the only circuitry in the SLA peculiar to an individual TWTA is the two printed circuit-board traces and one wire connecting that TWTA to the common +5 Vdc source used to provide the ON command voltage for all TWTAs.

1.5.2 Telemetry Interface

Five telemetry measurements are avialable from each HLTWTA: input current, helix voltage, filament voltage, helix current, and cathode current. Interface schematics for each of these measurements are shown in Figures 1.5-3 through 1.5-7. The detailed operation of these measurement circuits was discussed in Section 1.4. It should be noted that helix current, cathode current, helix voltage, and filament voltage measurements are cross-strapped in the satellite harness with the corresponding measurement from the redundant amplifier. Since only one of each pair of redundant amplifiers is on at a time, the effect of this cross-strapping is to place a parallel passive resistive load across the telemetry output of the operating tube. The effect of this parallel load on measurement accuracy is accounted for when the telemetry circuits are calibrated by the amplifier vendor.

1.5.3 Structural Interface

The TWTAs are mounted to the satellite with a combination of four screws inserted through feet on the amplifier chassis into platform inserts, and four screws inserted through a satellite platform heat sink into the base of the TWTA. The mounting details are illustrated in Figure 1.5-8. Since the TWTAs are received from the vendor with all screws used to hold the TWT to the amplifier chassis in place, it is necessary to first remove four screws from the TWTA.

The HLTWTA is inverted and placed on a soft mat on top of a workbench so that clear access to the base is available. Four 8-32 x 5/16 torque-set countersink head screws are then removed from the base and four plugs

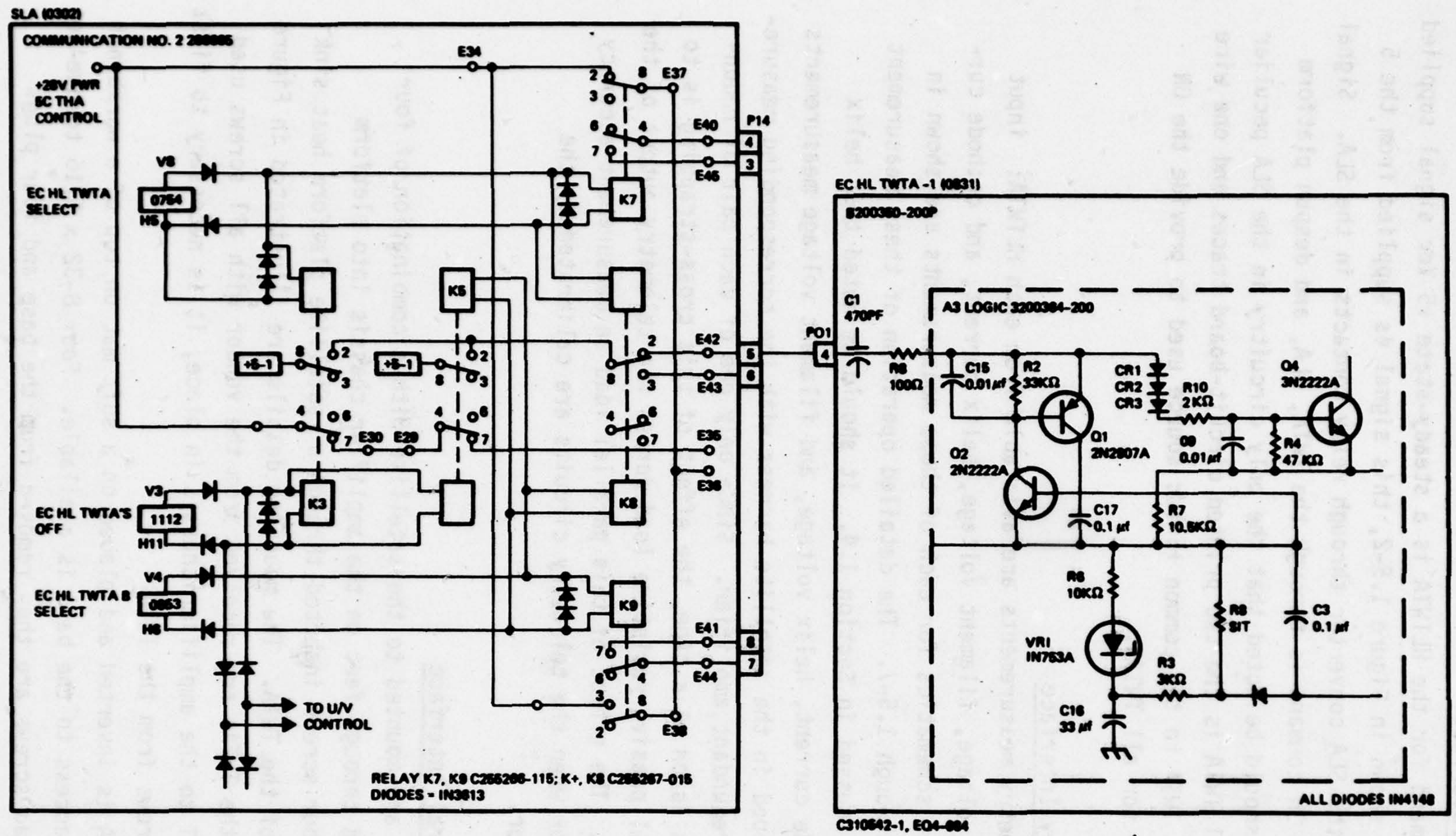

Figure 1.5-2. HLTWTA Command Interface Schematic (ECHLTWTA-1 Shown, Typical for All Four HLTWTAs)

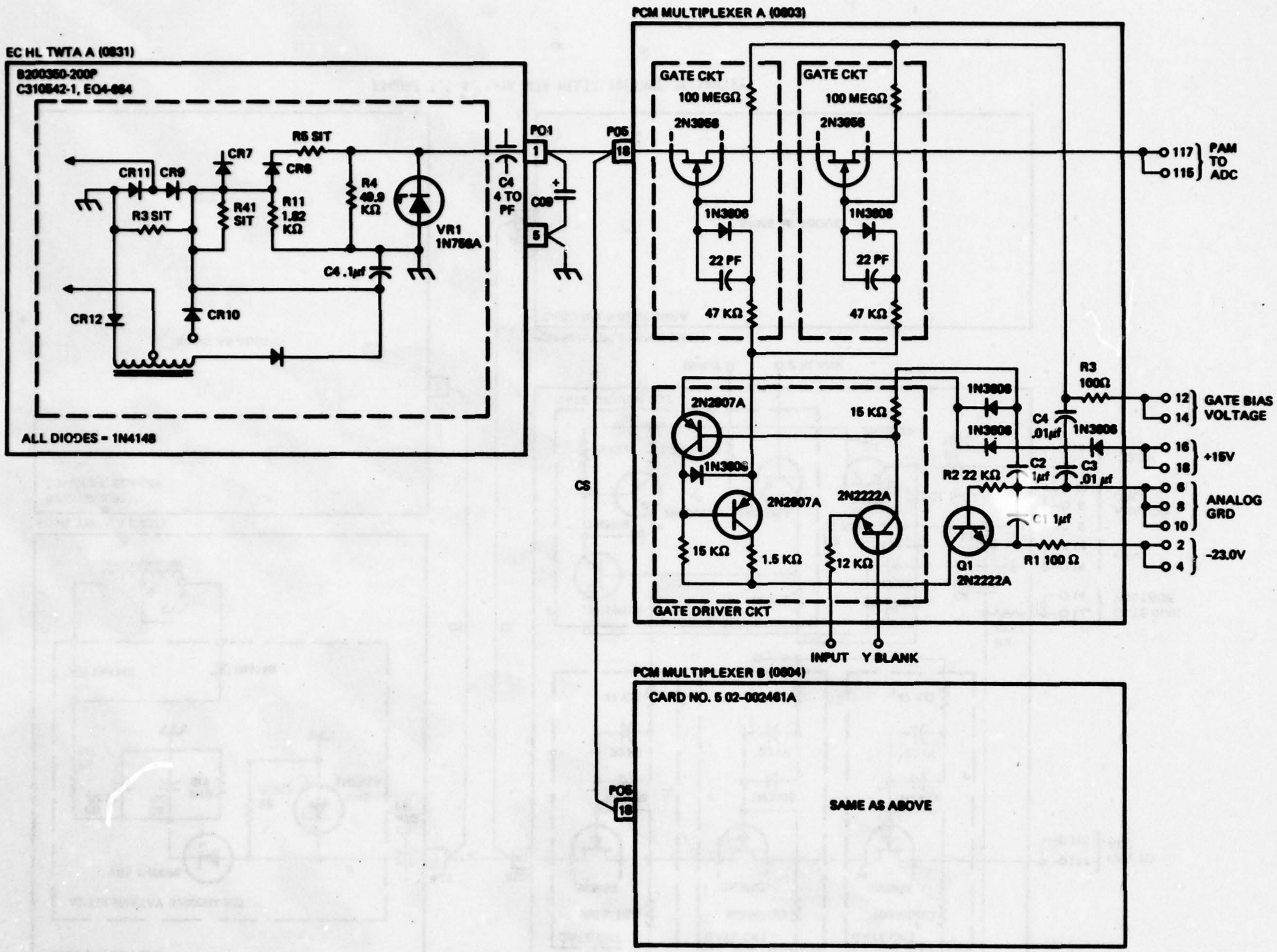

FIGURE 1.5-3. HLTWTA INPUT CURRENT TELEMETRY

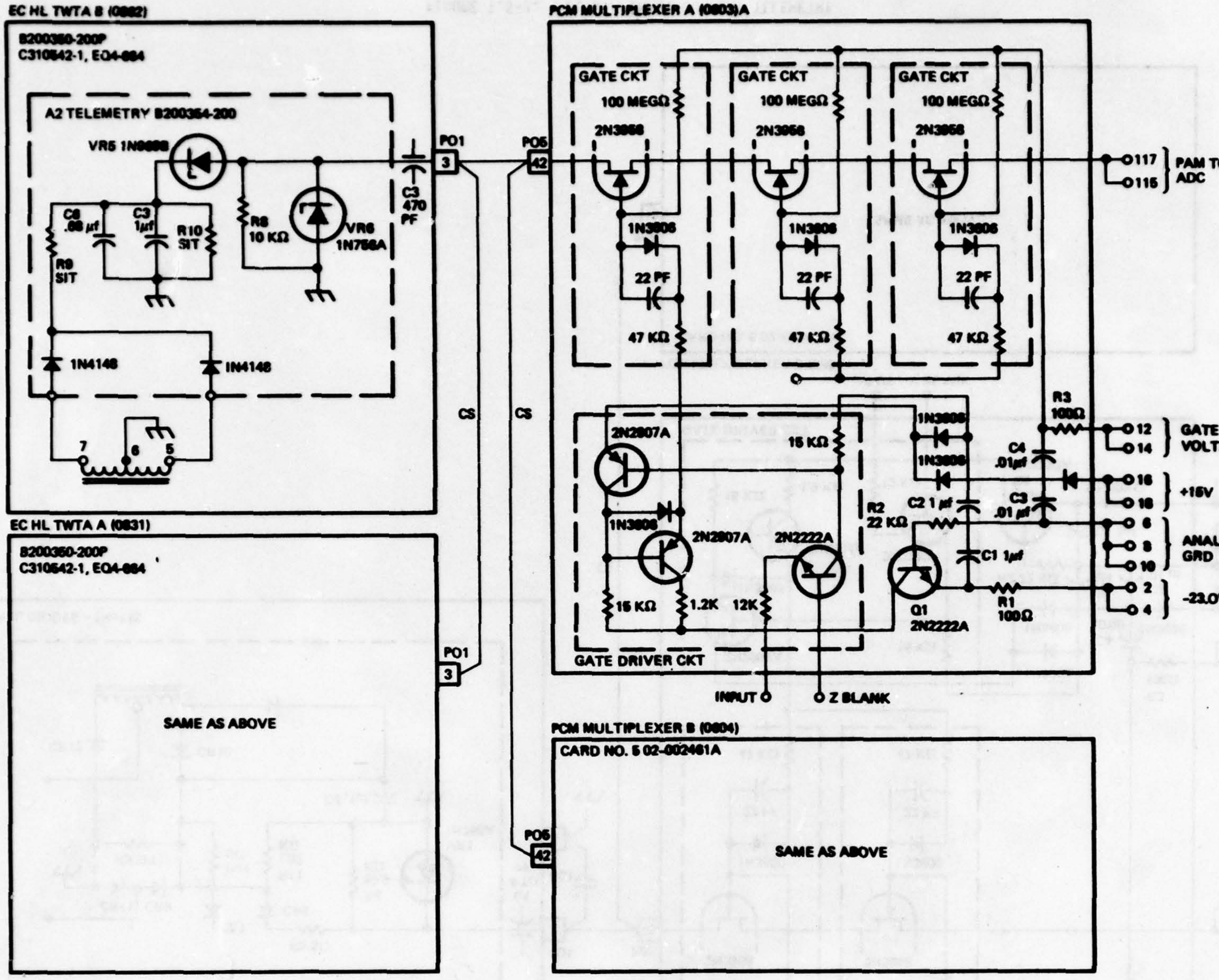

FIGURE 1.5-4. HLTWTA HELIX VOLTAGE TELEMETRY

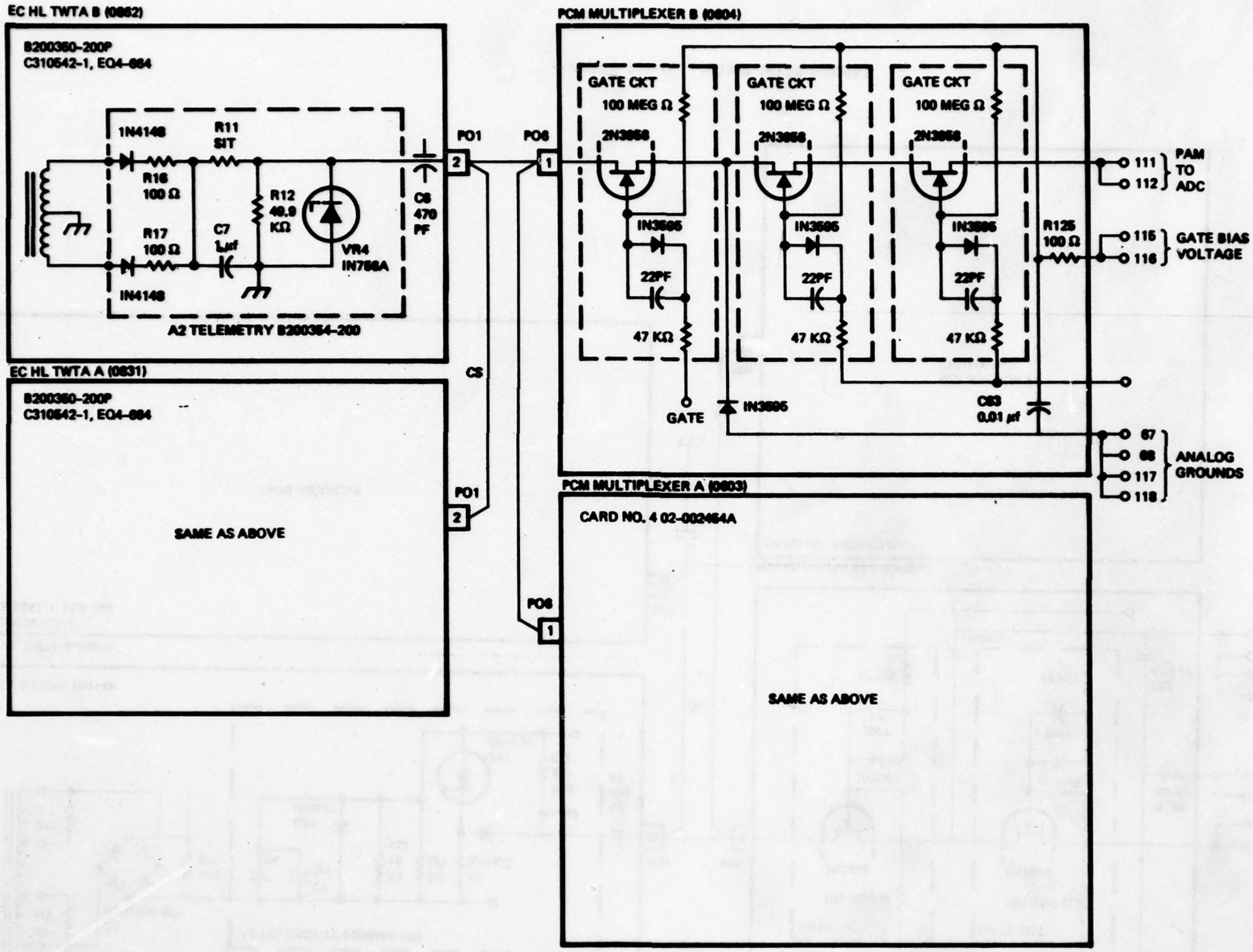

FIGURE 1.5-5. HLTWTA FILAMENT VOLTAGE TELEMETRY

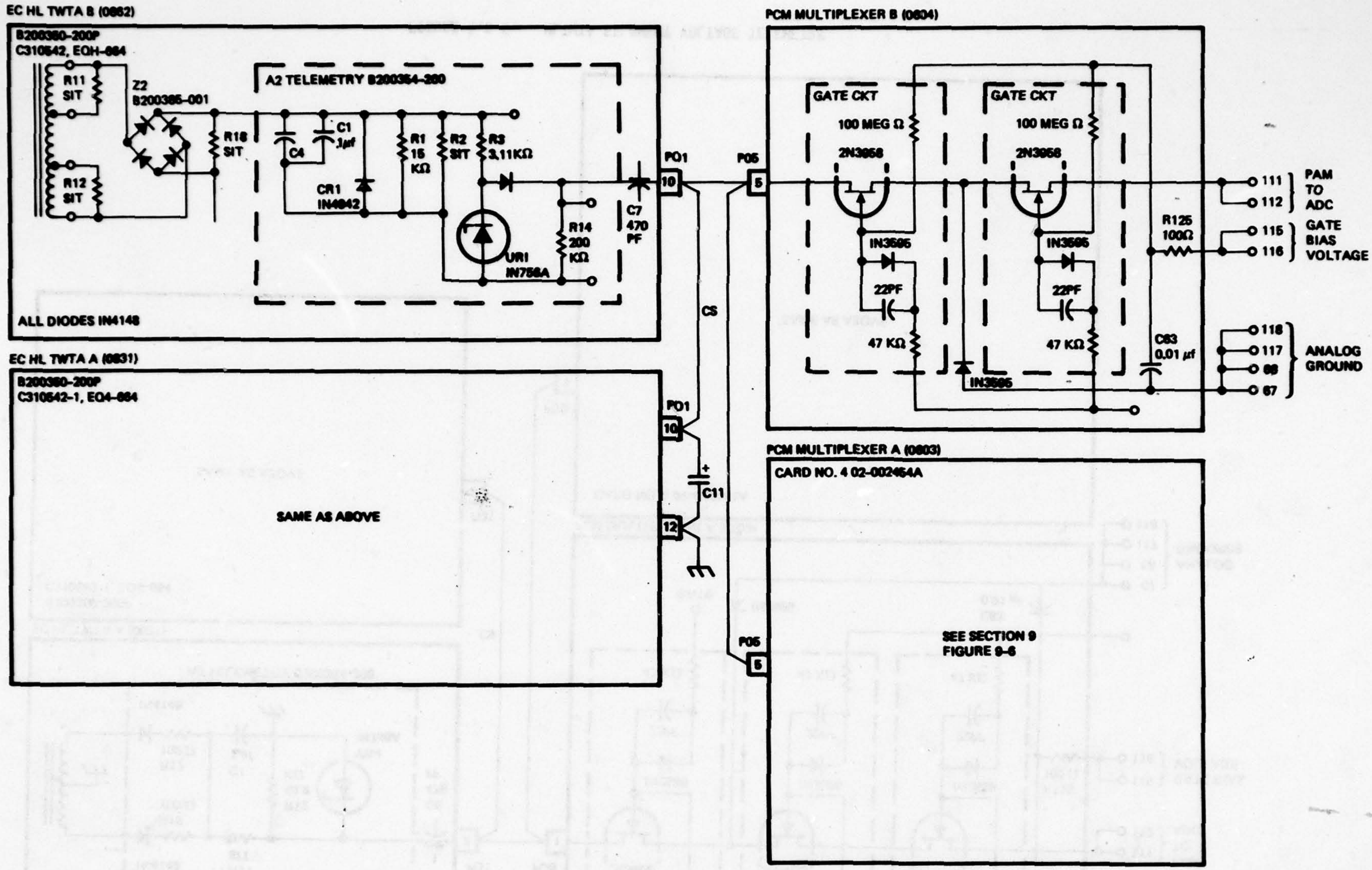

FIGURE 1.5-6. HLTWTA HELIX CURRENT

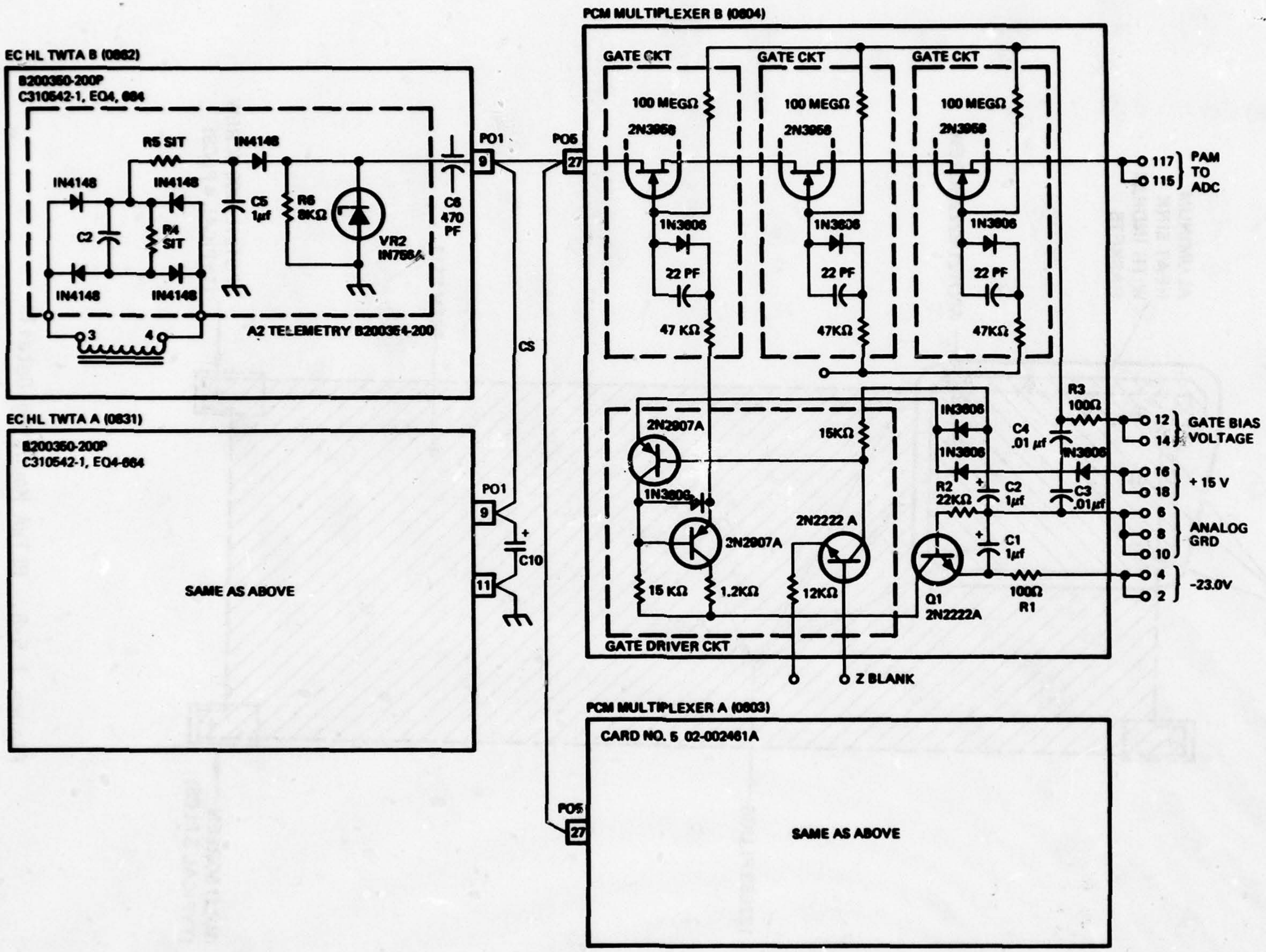

FIGURE 1.5-7. HLTWTA CATHODE CURRENT TELEMETRY

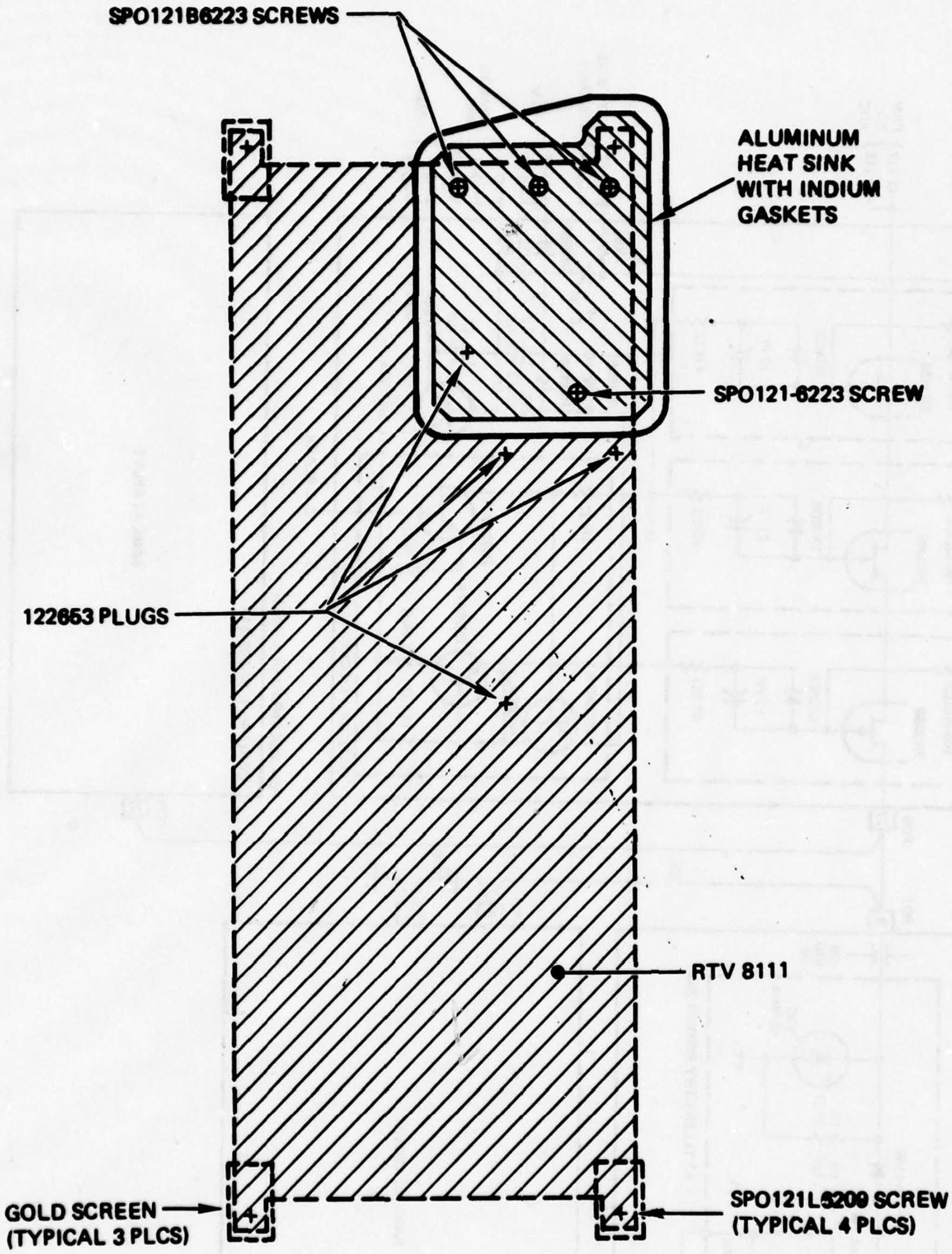

Figure 1.5-8. HLTWA Mounting Details

installed. The four threaded holes filled by plugs are used to secure the TWTA to a unit-level mounting base for heat-transfer purposes. They are not used to secure the TWT to the TWTA baseplate. These plugs are inserted into the amplifier base and set so that the top of the plug is 0.030 to 0.050 inch below the plane of the tube base. A silver-filled epoxy (Eccobond 56C) is then applied to the recess area over the plug head until the epoxy is built up to be flush to 0.020 inch below the plane of the tube base. The plug and epoxy serve as an RF shield.

The HLTWTA is then installed onto the despun platform. Indium gasketing is first placed on the aluminum heat sink of the despun platform. An RTV compound (RTV-8111) is then spread over the area on the despun platform where the tube will be installed. Three gold screens are placed over the platform inserts, and the tube is lowered onto the platform and secured with four SP0121L6209 screws.

From the bottom of the platform, four other screws (one SP01216223 and three SP0121B6223) are inserted through the aluminum heat sink, through the indium gasketing, and into the tube. These screws are then torqued to 11 to 13 inch-pounds for the first time. After 24 hours, they are retorqued, and after 2 weeks, they are torqued for the last time. The gasketing, aluminum heat sink, and 6223 screws are used to obtain heat transfer when the tube is installed on the satellite.

The mounting configuration for the HLTWTAs is controlled by Drawing No. 310511, Installation - Despun Platform, and is performed in accordance with procedure DR-215-11.

The indium gaskets and aluminum heat sink employed in mounting the amplifier to the despun platform are there to provide the necessary cooling of the collector and of the TWT, where as much as 80 watts of power can be dissipated. Thermal control provisions for the HLTWTA are discussed in Section 1.5.4.

1.5.4 Thermal Interface

The critical thermal control situation for the HLTWTAs exists in providing an acceptably low resistance thermal path for the heat dissipated in the TWT collector. Within the TWT, this is accomplished by soldering the collector end of the TWT into a copper saddle heat sink. The heat sink is then soldered to a copper plated BeO insulator. This assembly is soldered to the aluminum TWT base. The TWTA is secured to the amplifier

chassis with screws and employs a 0.005-inch gasket between the TWT and the amplifier baseplate.

The TWT is mounted to an aluminum fin built into the despun platform as shown in Figure 1.5-9.

Indium gaskets in the configuration shown in Figure 1.5-10 are used to provide good thermal conductivity from the amplifier baseplate to the platform fin. As seen in Figures 1.5-9 and 1.5-10, the aluminum fin extends through the platform as a large plug in the area under the collector end of the TWT. This thermal control scheme maintained the worst-case predicted baseplate temperatures as shown in Figure 1.5-11. The F8 NCHLTWTA temperatures interpolated from the flight telemetry sensor are, as expected, lower than worst-case predicted and are also shown in Figure 1.5-11.

1.5.5 Electrical Power Interface

Fused primary power is distributed to each HLTWTA independently from the Power Distribution Unit (PDU) on the spinning platform. Details of this distribution scheme are shown in Figure 1.5-12. Primary power from the PCU is regulated at 32.4 +0.2 Vdc whenever the satellite is in sunlight not recharging the batteries after an eclipse. During each eclipse and for several hours thereafter, the primary bus goes through one voltage cycle from 32.4 volts to approximately 26 volts and back to 32 volts. This voltage cycle occurs 45 times in one eclipse season, two eclipse seasons per year.

The nominal primary current load at 32.4 volts is three amperes for a HLTWTA. This current increases to about 3.75 amperes when the bus voltage decreases to 26 volts in a 72-minute eclipse. The slip rings are rated for continuous operation at three amperes each. Two are used in parallel for each TWTA.

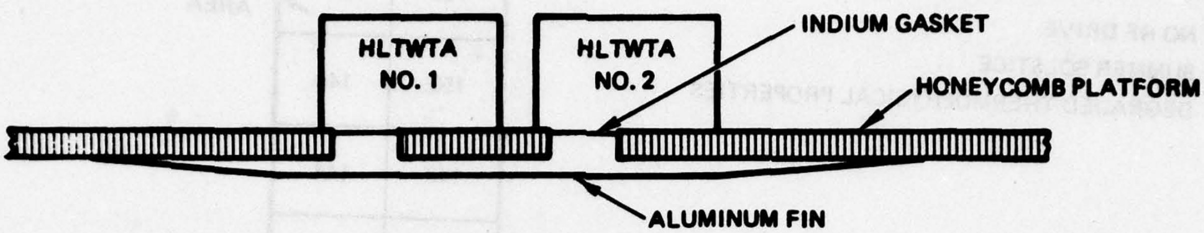

Figure 1.5-9. HLTWA/Spacecraft Interface Thermal Design

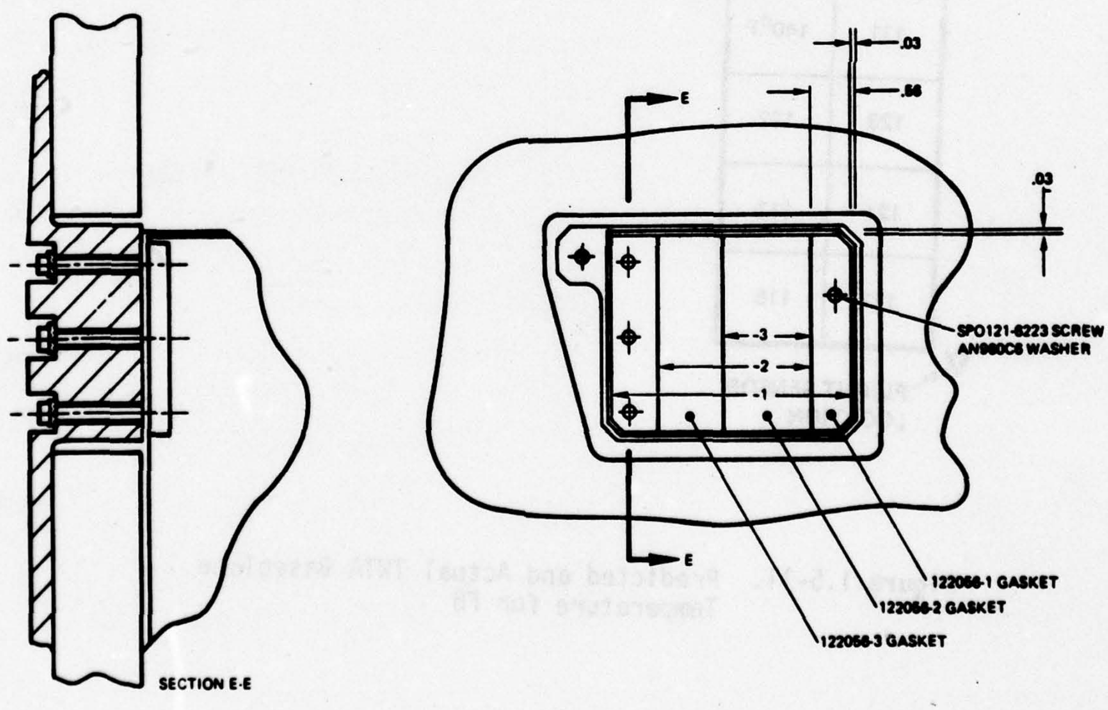

Figure 1.5-10. Indium Gasket Configuration, Satellites F1 — F8

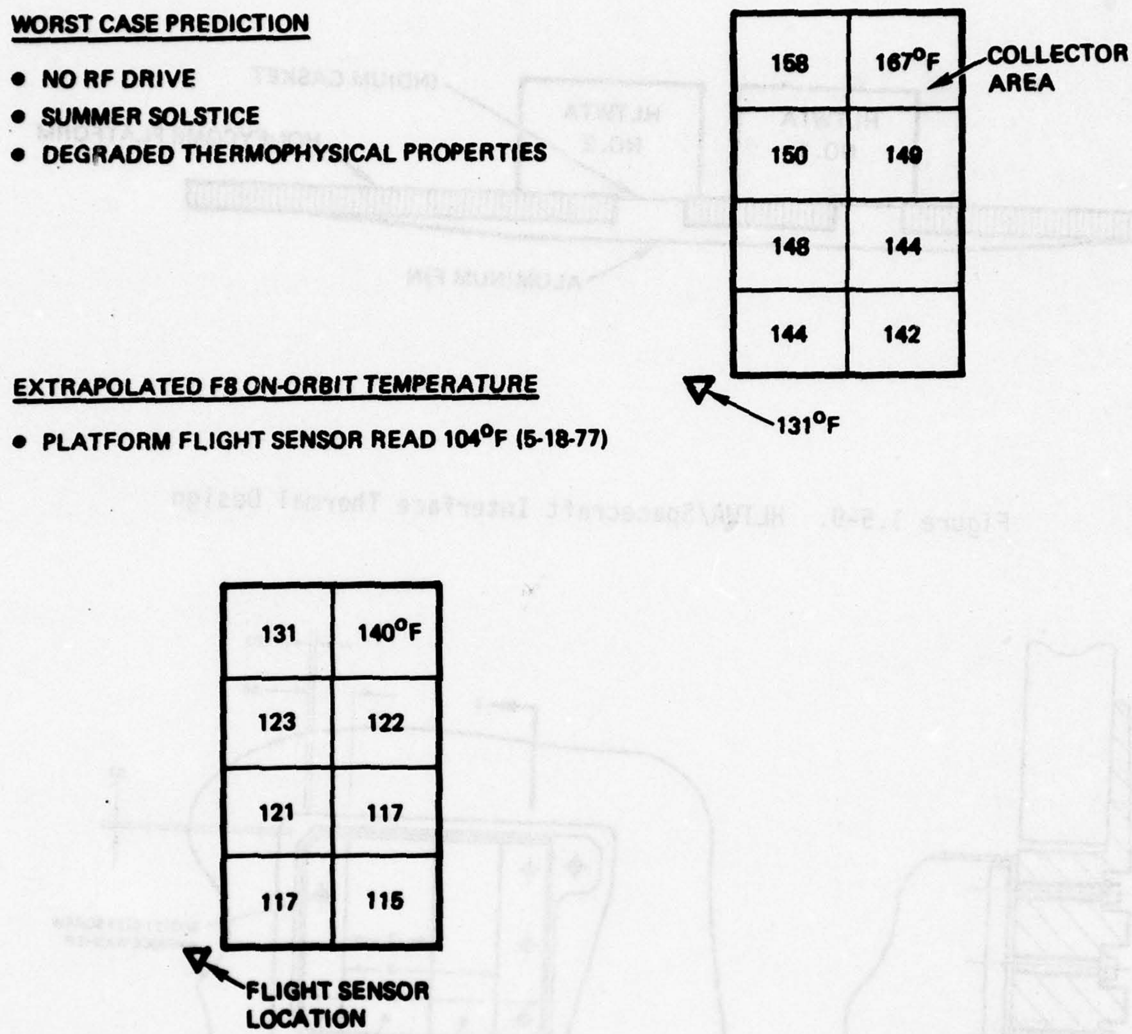

Figure 1.5-11. Predicted and Actual TWTA Baseplate Temperature for F8

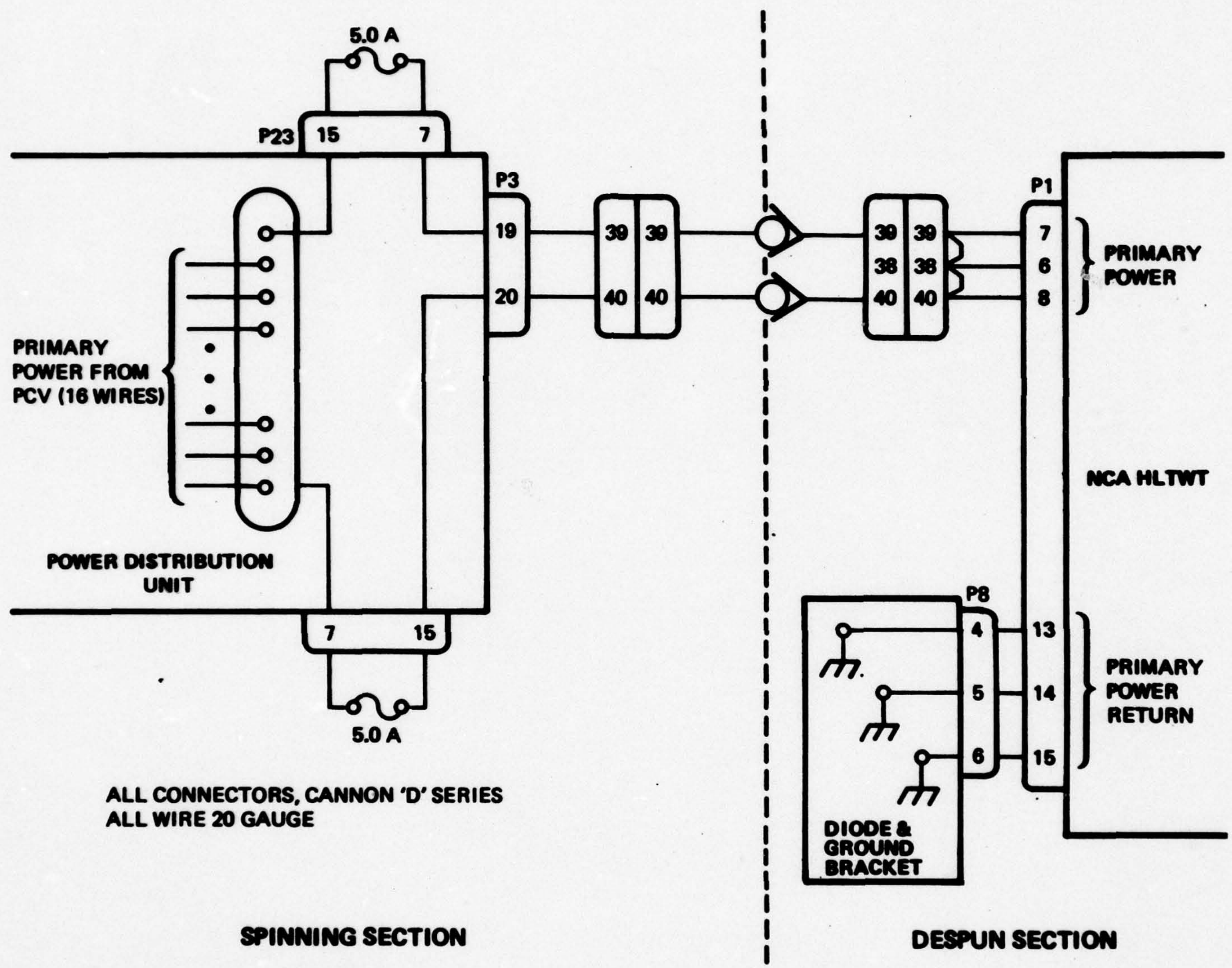

Figure 1.5-12. HLTWTA Power Distribution Schematic

2. ORBITAL CHRONOLOGY

2. ORBITAL CHRONOLOGY

Six 777 communication satellites have been successfully placed in orbit since November 1971. Three have experienced failure of one or more HLTWTAs. One ECHLTWTA failed on Satellites 9431 and 9434, and one NCHLTWTA failed on satellites 9434 and 9438. The shortest orbit-time-to-failure was 6 days (9438), and the longest 3.3 years (9434). A detailed chronology leading up to each of these failures is contained in the following paragraphs.

2.1 SATELLITE 9438 NCHLTWTA-1 CHRONOLOGY

Satellite 9438 was launched 12 May 1977 and placed in orbit the same day. An overall chronology of events from launch through HLTWTA failure is given in Table 2.1-1. Satellite 9438 communications testing started 25 May, with the satellite at the test station of 105 degrees west longitude. Preliminary results indicate nominal communications performance.

On 20 May, at 0806Z NCHLTWTA-1 turned itself off. Several attempts were made to command it back on. In each attempt, the amplifier responded to the ON command for the duration of the high-voltage delay timer, then turned itself off at high-voltage turn-on. A detailed chronology of the TWTA failure and subsequent recovery attempts is given in Table 2.1-2.

On-orbit communications testing of the F7 (9437) and F8 (9438) satellites was performed at Camp Parks Radiometric Station in Pleasanton, California during the second half of May and early June 1977. The following parameters were measured on both satellites:

a) Communications EIRP

b) Beacon EIRP

c) Gain transfer (high, nominal, and low gain states)

d) Beacon transfer

e) Channel gain control

f) EC (earth coverage) beacon frequencies

g) NC (narrow coverage) and AC (area coverage) antenna pointing.

Table 2.1-1. Satellite 9438: Overall Chronology (5/12 to 6/9)

Date	Time (Z)	Events
5/12/77	1427:01.661	Liftoff
	1558	Telemetry acquisition
	2106:44.7	Separation
	2239:04	Earth sensor N1 ON
	2241:18	Earth sensor S1 ON
		Platform despin rate mode convenience
5/13	0326:42	NC antennas erected
	0330:16	Boom deployment
	0344:18	Low level comm units ON
	1130-1254	TT&C redundancy test No. 1 (sequence C)
5/14	0610-0745	$\Delta\phi$ Maneuver No. 1 of 2
		$\Delta\phi$ Maneuver No. 2 of 2
	1652:41	DEA normal mode (sequence B)
	1746:25	HLTWTAs ON (sequence E)
5/15	0635-0815	NCS stops calibration (sequence L)
	2230-0110	Controls redundancy and clock calibration (sequence D and H)
5/17	1530-1830	TT&C test No. 2 (sequence F and G)
5/19	1200-2310	ΔV No. 1 (stopping burn)
5/20	0807:37	NCHLTWTA 1 failed
5/20 to 5/23	--	Repeated attempts to command NCHLTWTA 1 ON
5/21	2155-2245	ΔV No. 2 and $\Delta\phi$ No. 3 (ON-test-station)
5/25	1803:46	Roll comp ON
	1800-1900	Roll comp initialization (sequence I)
	2056	Start comm subsystem testing
5/26	1856	DEA gain 6
5/27	1431	DEA gain 5
5/31	1530-1630	DEA to gain state 4
6/1	1450	NCHLTWTA No. 2 ON
6/1	2115-2215	DEA to gain state 5
6/8	1720-2100	NCA pointing tests using DEA 1 and DEA 2
6/9	1830-1900	Comm testing completed

Table 2.1-2. Satellite 9438: HLTWTA S/N 24-17 Failure Chronology

Date	Time (Z)	Events
5/20/77	0806Z	NCHL-1 turned itself OFF.
	1504Z	NCHL-1 commanded ON. Turned OFF at HV turn-on. Camp parks had uplink carrier ON but observed no signal from satellite.
	1533Z	NCHL-1 commanded ON. Turned OFF at HV turn-on.
	2345Z	Set NN and EN gains to -12 dB and turned OFF NC beacon. NCHL-1 commanded ON. Turned OFF at HV turn-on.
		NCHL-1 commanded ON, using ON-OFF-ON command sequence. Same result.
5/21	0725Z	Repeated turn-on attempts of 20/2345Z.
	1315Z	Repeated turn-on attempts of 20/2345Z.
	1930Z	NCHL-1 commanded ON, using ON-OFF-ON (11 total commands, six ON, five OFF) at approximately 8-second spacing. Same result.
		NCHL-1 commanded ON, using block command (11 total commands, as above) at 300 mA spacing. Same result.
		Repeated block command, same result.
	2156Z	NCHL-1 commanded ON to turn the THA OFF for lower temperature.
5/22	000Z	NCHL-1 commanded ON, using OFF-ON commands prior to time-out for HV, 12 repetitions. Same results.
	0140Z	Same as 0000Z, except five repetitions.
	0715Z	Same as 0140Z.
	1315Z	Same as 0140Z.
	1930Z	Same as 0140Z.
5/23/77	0250Z	Same as 0140Z.
	0910Z	Same as 0140Z.

Table 2.1-2. Satellite 9438: HLTWTA S/N 24-17 Failure Chronology (Continued)

Date	Time (Z)	Events
	1500Z	Same as 0140Z.
5/31		Same as 0140Z, except two repetitions. Camp parks had uplink carrier on but observed no signal from satellite.
6/1		NCHL-2 commanded ON. It is alive and well.

In addition, the following tests were performed on the F8 satellite:

a) Narrow-coverage and area-coverage interference patterns

b) Selected transfer characteristics for the evaluation of area-coverage antenna receive and transmit performance.

Test results indicated that both satellites were working nominally. Comparison with TRW data showed good agreement in all cases where "standard" (primary or redundant) configurations were tested. Where "mixed" configurations were tested (mixing primary and redundant units), no direct comparison with TRW data was possible.

All communications EIRP data recorded were well within specification. All gain data, for standard configurations tested, were either within specification or within less than 1 dB of TRW factory data.

2.2 SATELLITE 9434 HLTWTA CHRONOLOGIES

Two HLTWTA failures have occurred on Satellite 9434 since its launch in December 1973. The first occurred 17 August 1974 and the second 23 May 1977. An overall satellite chronology surrounding these two failures is given in Tables 2.2-1 and 2.2-2, respectively.

2.2.1 17 August 1974 ECHLTWTA-1 Anomaly

On 17 August, SLA converter-2 turned off, thus removing power from the secondary power bus supplying TWTA ON command voltages (comm bus). The slow decrease in voltage on the SLA converter +5 output allowed the undervoltage relay driver in the SLA to turn on and close the undervoltage relay, thus turning off all TWTAs. When ECHLTWTA-1 was commanded ON (after switching the comm bus to converter-1), turn-on proceeded normally through

Table 2.2-1. Satellite 9434: Chronology Surrounding 17 August 1974 ECHLTWTA Anomaly

Date	Time(Z)	Event
6/25	1915 - 1930	NCA 1 and 2 update + N/S advisory change w/moon counter
7/2	1910 - 1925	Sun-moon counter update
7/15	2135 - 2210	$\Delta\phi$ Maneuver, NCA 1 and 2 update
7/18	0610 - 0620 0655 - 0725 0820 - 0850 0920 - 1020	Special supports for correction of SLA-1 converter failure
7/20	1830 - 1920	Comm reconfiguration due to TDAL upset
7/20	2255 - 2335	Comm reconfiguration due to TDAL upset
7/23	1340 - 1355	N/S advisory change w/moon counter
7/25	0535 - 0620	NCA update
7/27	0325 - 0355	Comm reconfiguration due to TDAL upset
8/2	1750 - 1805	Batteries to mini-trickle charge mode
8/6	0535 - 0550	N/S advisory switch w/moon counter
8/15	1310 - 1430	NCA update, ΔV and $\Delta\phi$ maneuvers (all maneuvers)
8/17	1430 - 1755	SLA converter caused loss of communications. ECHLTWTA could not be restarted
8/18	1115 - 1220 1345 - 1415 1605 - 1720 1730 - 2220	Comm reconfiguration plus second SLA converter switching event
8/19	1335 - 1410	N/S advisory switch w/moon counter
8/21	1815 - 1900	NCA repointing and programmer update
8/24	1334 - 1430	TDAL gain upset and reconfiguration
8/25	1820 - 2005	Comm reconfiguration for third SLA converter switching event
8/29	1400 - 1415	Sun/moon counter update

Table 2.2-1. Satellite 9434: Chronology Surrounding 17 August 1974 ECHLTWTA Anomaly (Continued)

Date	Time(Z)	Event
9/3	2140 - 2345	TDAL gain upset and reconfiguration SLA converter event No. 4
9/5	1200 - 1235	First eclipse support
9/6	2240 - 2255	TLM transmitter No. 1 select
9/19	0015 - 0100	$\Delta\phi$ Stationkeeping and NCA update
9/20	1330	DEA - standby mode Spacecraft spun-up (CMD execute No. 1) ACS reconfigured to normal mode on ACS bus No. 1
9/21	0200 - 0235	NCAs repointed due to spin-up, sun/moon counters updated
9/23	0500 - 0545	TDAL lag change
9/23	2100 - 2145	NCA No. 2 repointed to Guam (Wang)
9/24	0240 - 0300	NCA No. 2 updated (CMP)
9/26	1515 - 1930	Spacecraft spin-up (CMD execute No. 2) ACS reconfigured to normal mode using CTA-1
10/1	1105 - 1230	ACS CMD execute anomaly No. 3 ACS reconfigured and NCA update performed.

Table 2.2-2. Satellite 9434: Chronology Surrounding 23 May 1977 NCHLTWTA Anomaly

Date	Time(Z)	Event
12 April	0025 - 0640	Batteries → mini-trickle charge mode
21 April	2156 - 2230	Sun/moon counter phase update
6 May	1130 - 1230	ΔV and $\Delta\phi$ maneuvers prior to summer solstice; NCA update w/programmer amplitudes set to zero
17 May	1610 - 1625	Power management, step No. 1 (encryptor bypass)
23 May	0808	NCHLTWTA No. 1 → OFF
23 May	0900 - 1020	NCHLTWTA No. 2 → ON
23 May	1940 - 1955	Power management, step 2 executed (RML/TLS OFF)
25 May	1345 - 1420	Power management, steps 3, 4 and 5, executed
26 May	2330 - 2345	Batteries → trickle charge mode
27 May	2005 - 2020	Batteries → auto-full charge mode
June	0350 - 0405	Bus limit → 33.4 volts, batteries to trickle charge mode
28 June	0400 - 0415	Multiplexer → ON

the 90-second timer period. At the end of that time, the high-voltage power supply turned on momentarily and the tube turned itself off. ECHLTWTA-2 was commanded ON and performed normally.

Essentially the same sequence of events occurred on 18 August, except that the comm bus was powered by converter-2 and no indication of high-voltage turn-on was available on telemetry.

A total of five attempts were made to restart the failed HLTWTA. In each case, the low-voltage (filament) power supply turned on for approximately 90 seconds (timer period), at which time the tube turned itself off. There was no indication on telemetry of high-voltage turn-on. The dates and times of these turn-on attempts are given in Table 2.2-3 below.

Table 2.2-3. ECHLTWTA S/N 14-10 Turn-On Attempts

8-17-74	1418Z	Comm bus off (converter anomaly) Comm subsystem OFF
	1723Z	ECHL-1 commanded ON Turned OFF at HV turn-on, but one sample of main bus current at that time showed elevated but less than nominal reading for ECHLTWTA ON.
	1800Z	ECHL-2 commanded ON
8-18-74	1736Z	ECHL-1 commanded ON Turned OFF
11-3-74	2155Z	ECHL-1 commanded ON Turned OFF at HV turn-on
11-8-74	0851Z	ECHL-1 commanded ON Turned OFF at HV turn-on
	1025Z	ECHL-1 commanded ON Turned OFF at HV turn-on

2.2.2 23 May 1977 NCHLTWTA-1 Anomaly

On 23 May NCHLTWTA-1 turned itself off. At that time it had been in operation continuously since launch in December 1973, a total of 3.5 years. Two attempts were made to turn it on. When both failed, the NCHLTWTA-2 was commanded ON and functioned normally. In both turn-on attempts, no measurable input current was drawn by the TWTA. The THA heaters were observed to go off as expected when a HLTWTA ON command was executed. Since 9434 is an operational satellite, no subsequent NCHLTWTA-1 turn-on has been attempted. The date and time of the two turn-on attempts are given in Table 2.2-4 below.

It can be seen from the above that the signature of the unsuccessful 23 May turn-on attempts differs from the other 777 HLTWTA failures. In this case, no input current was drawn after the turn-on command was executed in the SLA, whereas in all other cases, the data indicated the low-voltage portions of the power supply operated properly. It was only after the application of high-voltage that the TWTA shut itself off.

Table 2.2-4. NCHLTWTA-1, S/N 24-9 Turn-On Attempts

5-23-77	0808Z	NCHL-1 turned OFF
	0913Z	NCHL-1 commanded ON. Input current = 0
	0919Z	Same as 0913
	0928Z	NCHL-2 commanded ON

2.3 SATELLITE 9431 ECHLTWTA-1 CHRONOLOGY

On 21 December 1972, Satellite 9431 behaved normally with ECHLTWTA-1 transmitting. Some time between 0053:10 and 0053:18 (TMT) on 22 December 1972, transmission from this unit stopped and the beacon alarm was activated. Telemetry was being monitored by the Indian Ocean Station at that time. The sequence of events following ECHLTWTA-1 turn-off is summarized in Table 2.3-1, which shows that the spacecraft responded normally to reorientation commands and turn-on of the standby ECHLTWTA-2 without any difficulty. At the time of this failure, ECHLTWTA-1 had accumulated 9,129 hours of normal operation.

On 18 April 1973, an attempt was made to restart ECHLTWTA-1 after turning off ECHLTWTA-2. It was noted that normal input current was drawn

Table 2.3-1. Satellite 9431: Chronology of ECHLTWTA Anomaly

Date	Time (Z)	Event
12/21/72	2012:01	Start pass ECHLTWTA data normal throughout this pass
	2033:45	End of pass
12/22/72	0052:08	Start pass (Indian Ocean Station)
	0053:10-0053:18	EC HLTWTA-1 turn-off
	0100:55	Start contingency pass (Boss Station, no telemetry)
	0103:35	*9999 contingency block command transmitted (satellite → rate mode)
	0112:22	End of Indian Ocean Station data
12/22/72	0148:07	Start of Antigua data (with Boss)
	0208:59	End of Boss/Antigua pass
12/22/72	0254:27	Boss/Antigua special support
	0336:09	*7127 ECHLTWT-2 ON
	0342:16	*7127 Back-up command
	0355:39	*9977 Contingency block (returned controls subsystem to previous configuration)
	0407:10	*9977 Contingency block retransmitted
	0413:59	*0636 CTA Mode
	0432-59	*0466 DEA Mode → Normal
	0433:06	*0266 DEA Mode → Rate
	0434:10	*0366 DEA Mode → Search
	0434:47	*2115 Search Rate Bias
	0436:21	*0346 DEA Mode → Enable Normal
	0436:56	Change from Search Mode to Normal Mode
	0441:01	*0616 CTA Mode → Window ON
	0442:06	*2150 North Bias
	0443:51	*2945 South Bias
	0511:35	End of pass

*Command transmitted

during the 90-second warm-up period but abruptly dropped to zero during high-voltage turn-on. Heater voltage telemetry indicated that the power supply operated normally during the warm-up period.

After this unsuccessful attempt to restart ECHLTWTA-1, ECHLTWTA-2 was restarted successfully and operated properly until primary power to the despun section was interrupted prematurely in December 1973. The investigation conducted to determine the probable cause of this failure concluded that the available data "indicates that a failure occurred in the high-voltage section of the TWT power supply or in the traveling wave tube itself." There was no way to further localize that failure due to lack of telemetry voltage at the time of failure and due to the low sampling rate of the satellite telemetry system at the time of the restart attempt.

2.4 SATELLITE 9433 ECHLTWTA-2 CHRONOLOGY

Satellite 9433 had been in a nonoperative condition for some time prior to the May 1977 9438 HLTWTA failure. However, those HLTWTAs which were ON were operating nominally. In order to get an indication of what effects, if any, long term orbit storage had on a HLTWTA, and to ensure these TWTs would be operational if required, the redundant ECHLTWTA and NCHLTWTA were both commanded ON (one at a time) on June 29, 1977. The NC amplifier turned on nominally with no indication of anomalous behavior. All telemetered measurements were comparable to their values when this TWTA was last operated.

However, ECHLTWTA-2 did not turn on in a nominal manner. Two distinct anomalous conditions were noted:

a) The time between execution of the turn-on command and the first attempted application of high-voltage to the TWT by its power supply had increased from a nominal value of 90 seconds.

b) A total of nine input current pulses were observed before the TWTA high voltages actually came on and the tube began to operate. These pulses were approximately 30 seconds in duration, about 0.4 ampere in magnitude, and occurred at approximately 55-second intervals. The total time between execution of the ON command and completion of the TWT turn-on was about 625 seconds.

In reviewing telemetry data at the time of the TWT turn-on, it is also noted that there was no indicated high voltage during the 625 seconds in which the TWTA was attempting to turn on. Although there is no telemetry sample of high-voltage during each of the nine current pulses, there are measurements during three of the nine pulses with no indication of high-voltage being applied to the TWT.

It should also be noted that heater voltage actually decreased approximately 2.8 volts during the input current pulse. Again, data are available for only two of the nine pulses because of the infrequent sampling of heater current. Orbital data from the turn-on anomaly are plotted Figure 2.4-1. It should be noted that ECHLTWTA-2 did turn on eventually and has operated properly since June 1977.

3. ANALYSIS OF SELECTED ORBITAL AND GROUND TEST DATA

3. ANALYSIS OF SELECTED ORBITAL AND GROUND TEST DATA

Two characteristics of the HLTWTA orbit failures experienced on 777 satellites have been that they occur without apparent warning and usually at a time when no telemetry is being recorded by ground stations. Therefore, there is little direct orbit data to analyze. The quantity and, hence, usefulness of the orbit data are further reduced by the slow sampling rate used for most of the TWTA parameters which are telemetered.

3.1 ORBIT FAILURE EVENT DATA

The 9438 NCHLTWTA-1 failed at 29,136 seconds system time on 20 May 1977. Plots of the telemetry data for this amplifier up to the time of failure show no degradation or deviation from nominal levels for any of the telemetered parameters (Figure 3.1-1.)* Between two TWTA input current measurements 1 second apart, the current went from a nominal value of 2.9 to 0 amperes. Confirmation of this is provided by the main bus current measurement which indicated a similar drop in value between successive measurements. This measurement is taken at 8-second intervals, but occurs before and after the HLTWTA input current measurements. The variations observed on the main bus current measurements are primarily due to pulse loads in the despun controller and can be seen to exist both before and after the TWTA failure.

The fact that only one TWTA was affected by the anomaly demonstrates that the problem is not in the undervoltage sensor in the PCU or undervoltage control logic in the SLA, since operation or failure of this circuitry would have caused the simultaneous shutdown of both HL and LL EC and NCTWTAs.

The failure data alone indicate only that the HLTWTA is no longer operating and give very little clue to why. To begin to understand the

*This plot of orbit data and those in Figures 3.1-2 through 3.2-2 were provided by The Aerospace Corporation.

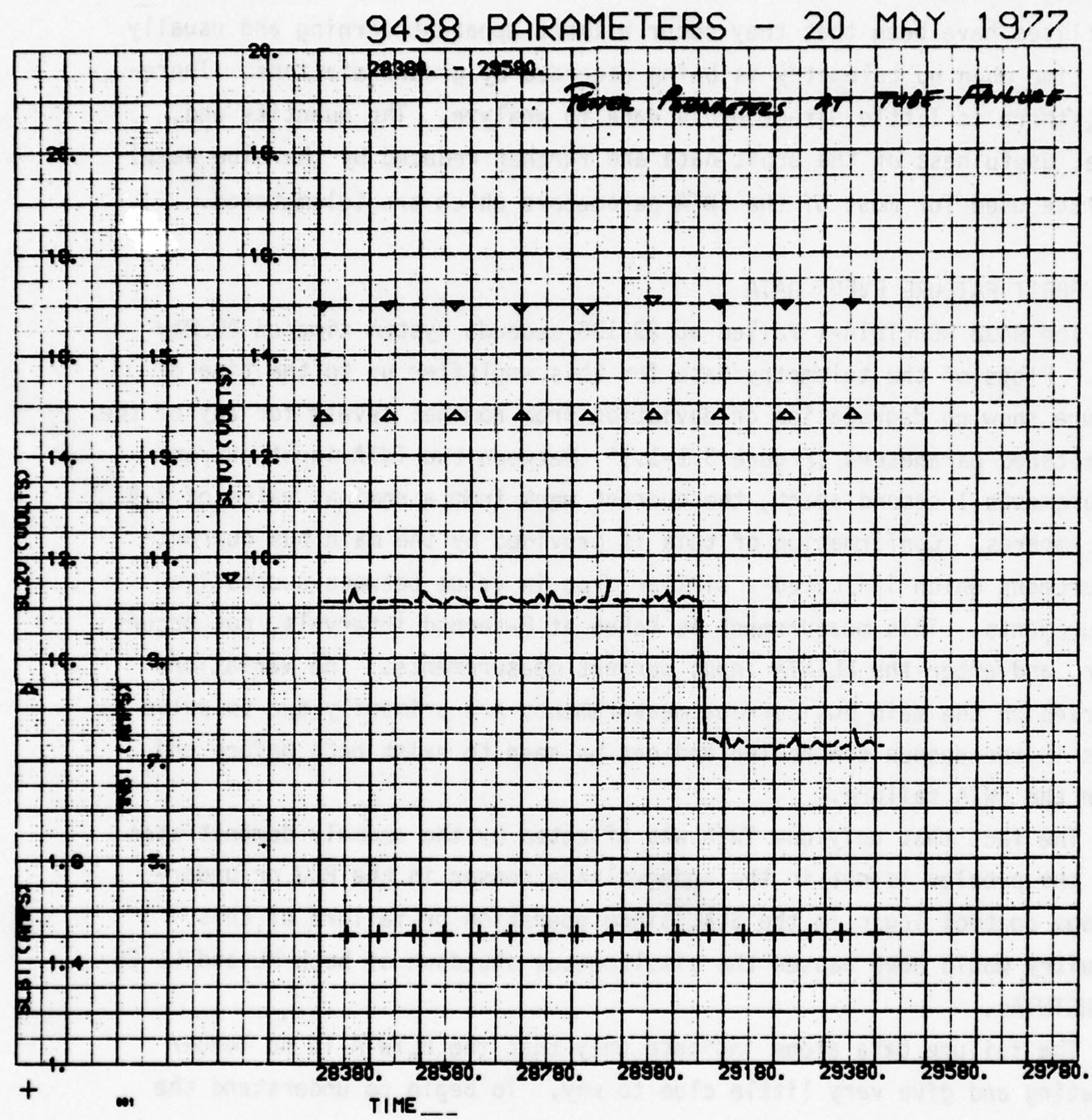

Figure 3.1-1. F8 HLTWTA-1 Parameters at Time of Orbit Failure (20 May 1977) Show Sudden Turn Off Without Warning

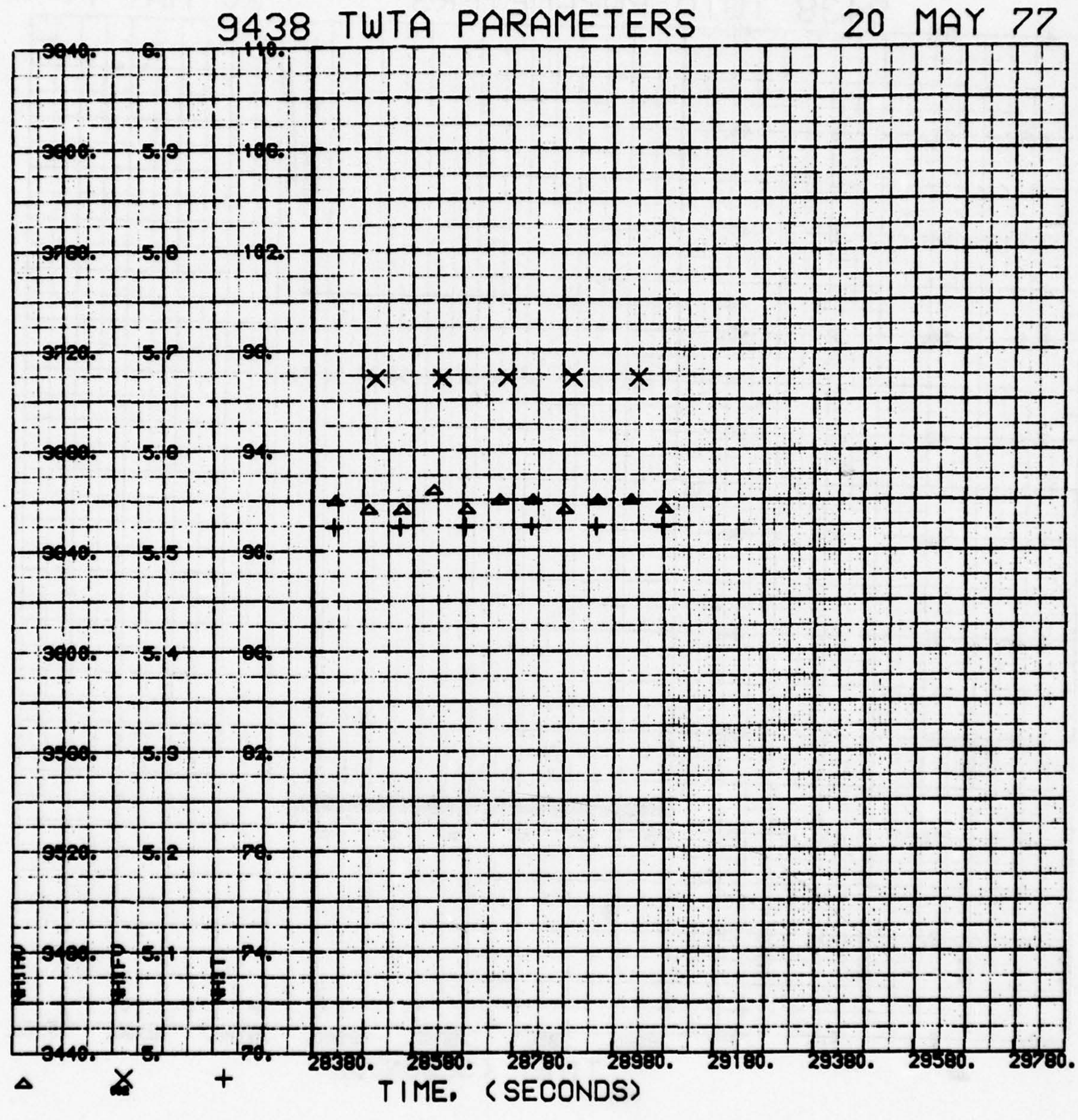

Figure 3.1-1. F8 HLTWTA-1 Parameters at Time of Orbit Failure (20 May 1977) Show Sudden Turn Off Without Warning (Continued)

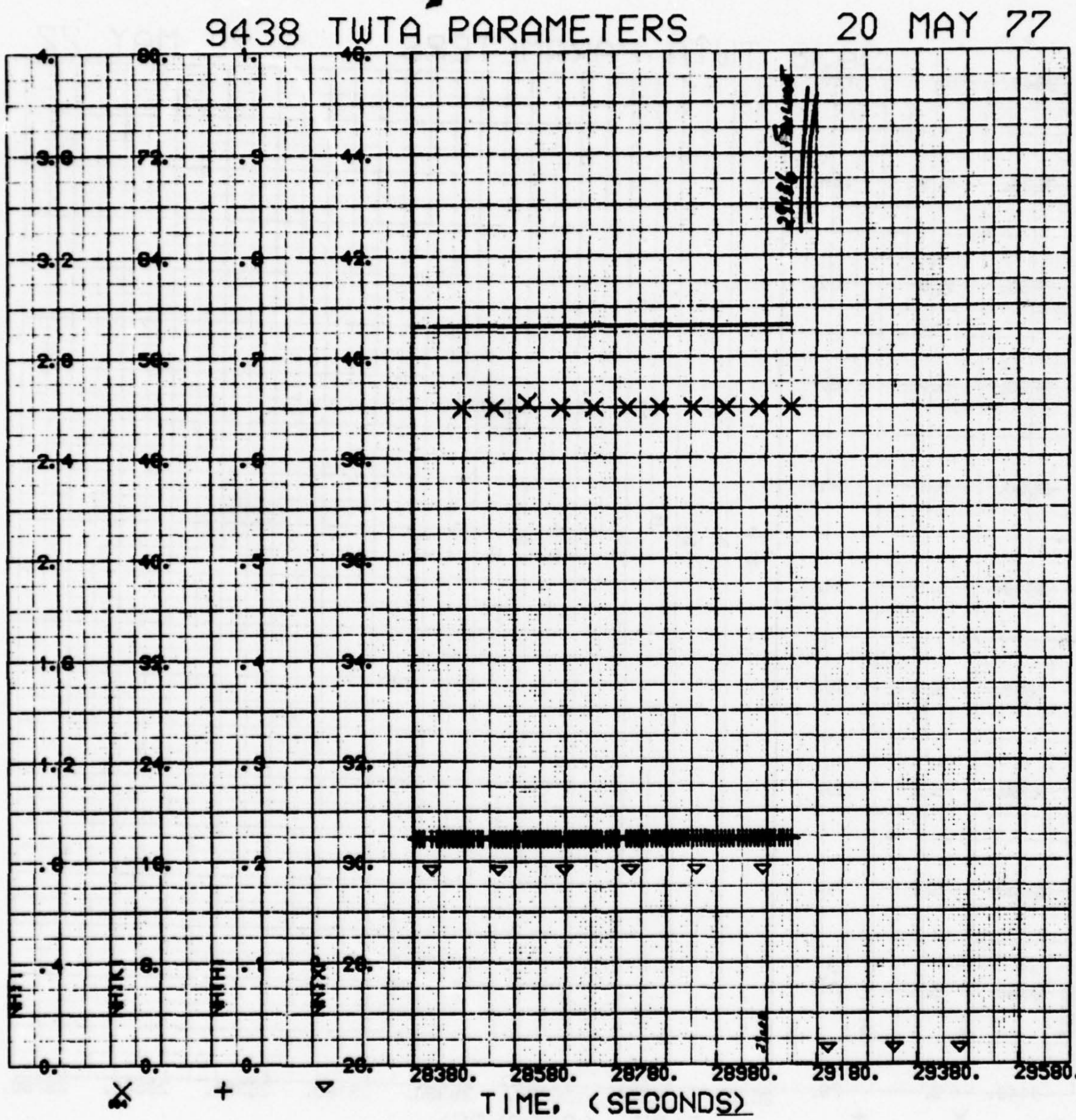

Figure 3.1-1. F8 HLTWTA-1 Parameters at Time of Orbit Failure (20 May 1977) Show Sudden Turn Off Without Warning (Continued)

anomaly, it was necessary to attempt to turn the TWTA on. This was first done approximately 25,000 seconds after the failure. At this turn-on attempt (Figure 3.1-2) and for all others attempted later (Appendix A-1), the HLTWTA response was similar: The power supply turned on and provided filament voltage to the TWT. After approximately 90 seconds, when the internal high voltage delay timer timed out, the amplifier immediately shut down. The high-voltage delay timer is designed for a nominal time delay between initial turn-on and application of high voltages to the TWT of 90 seconds. A review of the initial turn-on of this TWTA in orbit showed this time delay had not changed from previous operation (Figure 3.1-3). A total of 11 turn-on attempts were made on 20 and 21 May 1977, all with the same result.

Using special command sequences, an attempt was made to cause a variation in the delay between initial amplifier turn-on and application of the high voltage to the TWT. By using a special sequence of ON and OFF commands spaced at 300 msec intervals, this warm-up time was extended to approximately 200 seconds, twice the nominal 90-second interval. However, the outcome was unchanged. At application of high voltage, the amplifier shut itself off immediately. No RF energy was detected by ground stations.

The orbital evidence indicates with high confidence that large segments of the TWT power supply are operating correctly. It is concluded that the failure is most likely in the high-voltage section of the power supply, the helix overcurrent trip circuit, or the TWT itself, based on the following considerations:

a) The TWTA turn-off latch circuitry did operate to clear the input power bus.

b) When turn-on commands are sent, the protective latch releases and the unit starts.

c) The high-voltage turn-on delay timing period is nominal. Thus, the internal 19-volt bus in the power supply is regulating, and hence all signal conditioning circuitry in the control loop is functional.

d) The heater current is normal during the 90-second warm-up period.

Consequently, the anomaly investigation concentrated its activities on trying to determine a probable cause for the failure within the high-

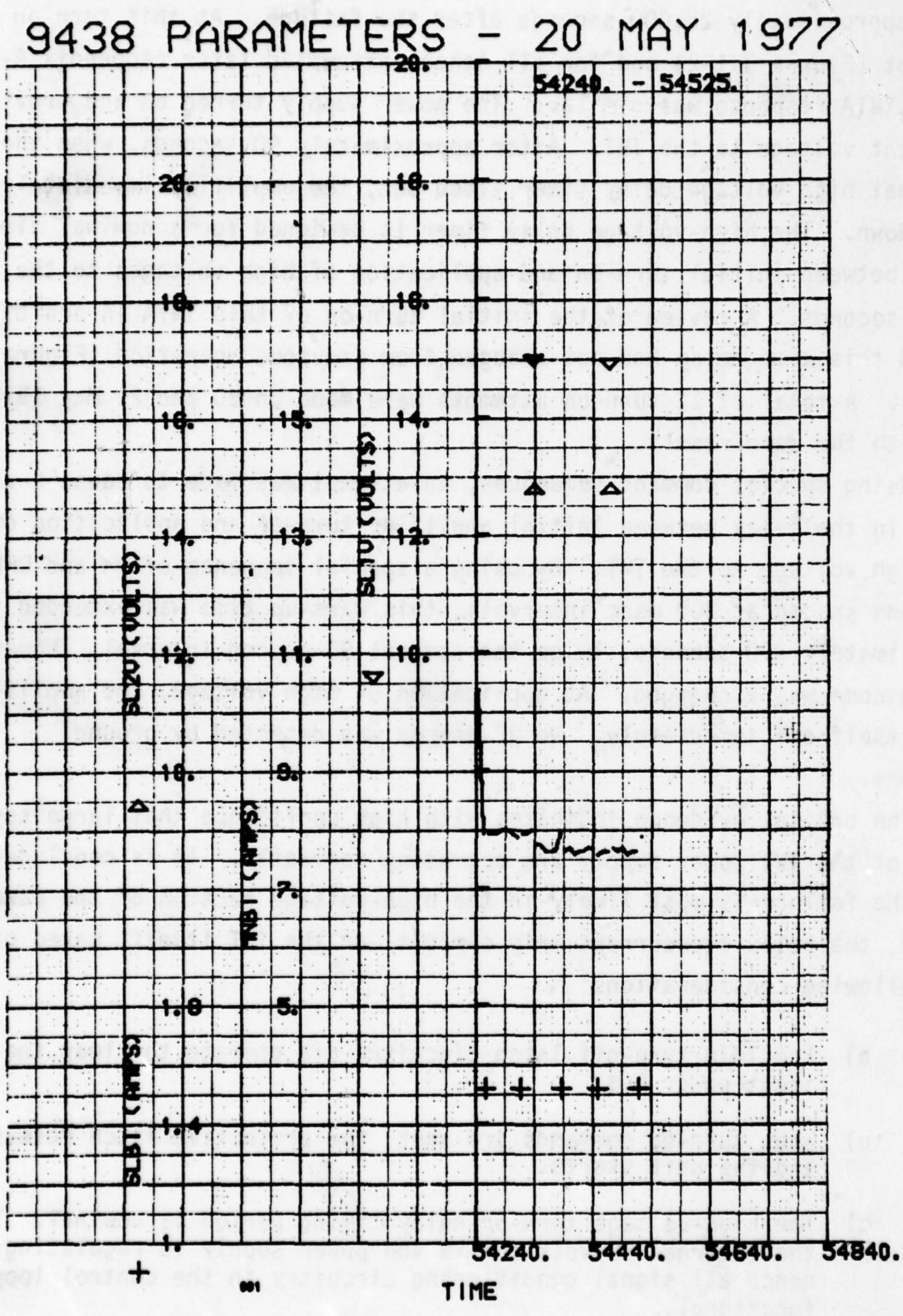

Figure 3.1-2. F8 HLTWTA-1 Parameters at First Turn On Attempt Show Nominal Operation Until the Instant of Application of High Voltage (The Amplifier Shutdown Immediately Thereafter)

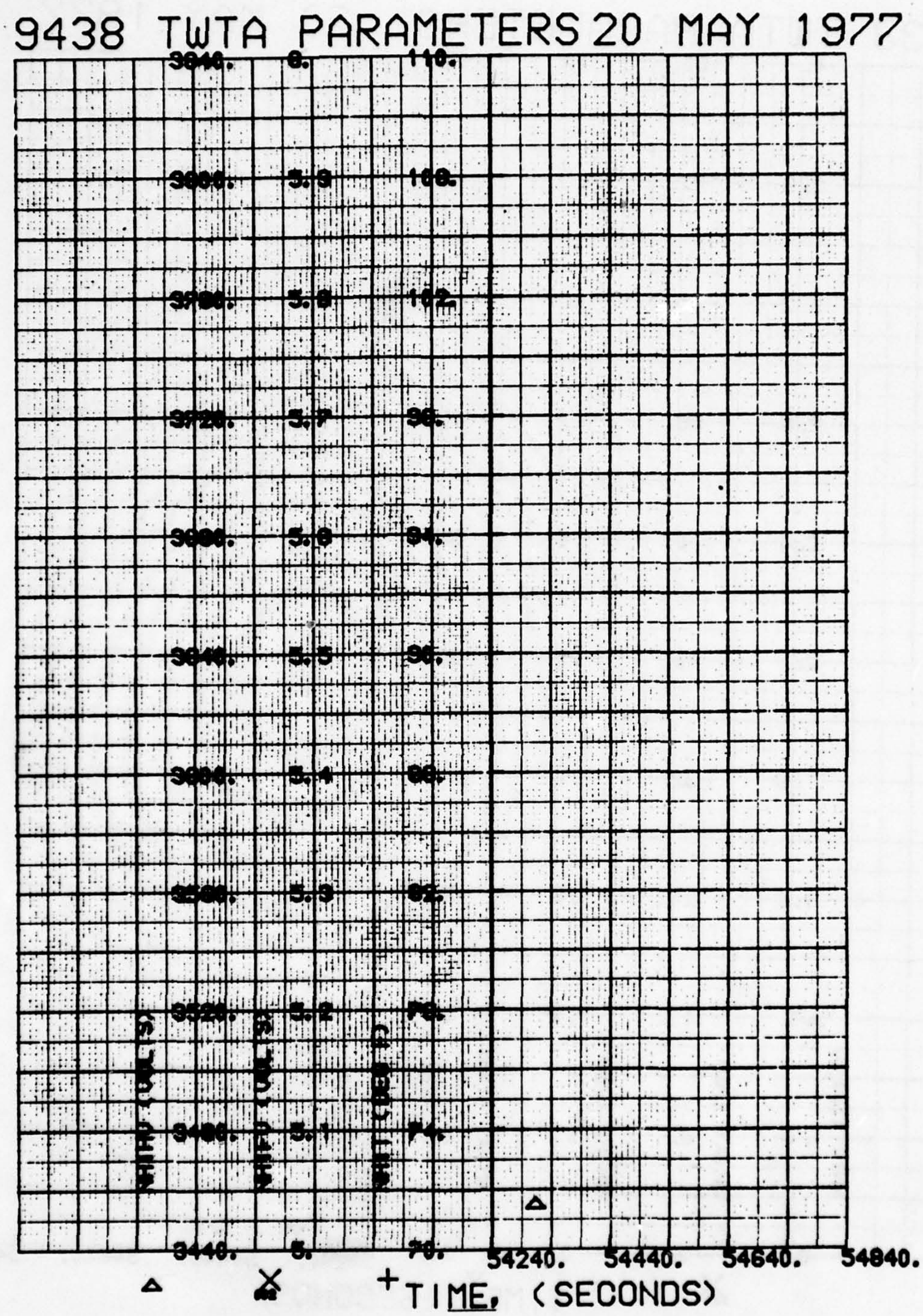

Figure 3.1-2. F8 HLTWTA-1 Parameters at First Turn On Attempt Show Nominal Operation Until the Instant of Application of High Voltage (The Amplifier Shutdown Immediately Thereafter) (Continued)

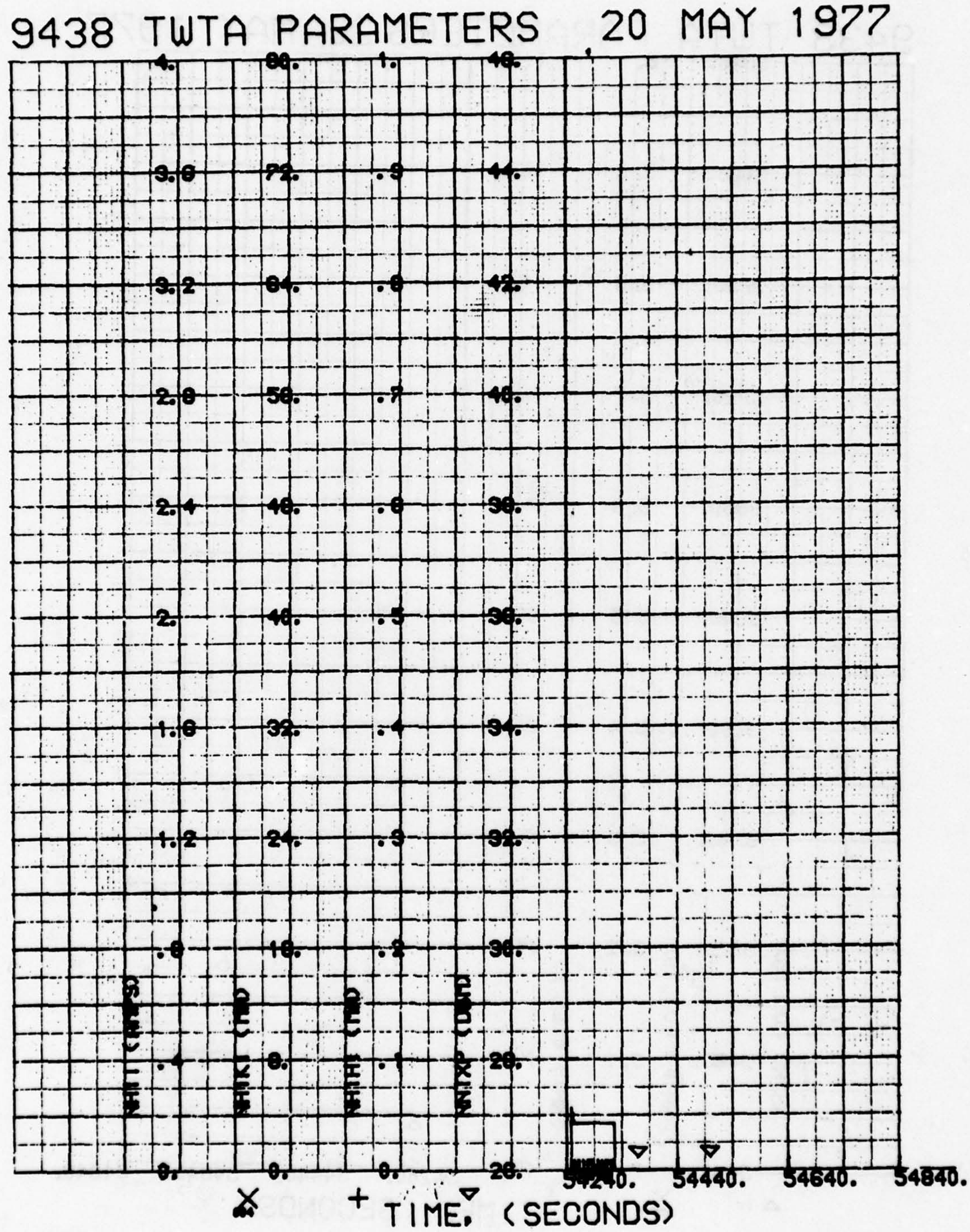

Figure 3.1-2. F8 HLTWTA-1 Parameters at First Turn On Attempt Show Nominal Operation Until the Instant of Application of High Voltage (The Amplifier Shutdown Immediately Thereafter) (Continued)

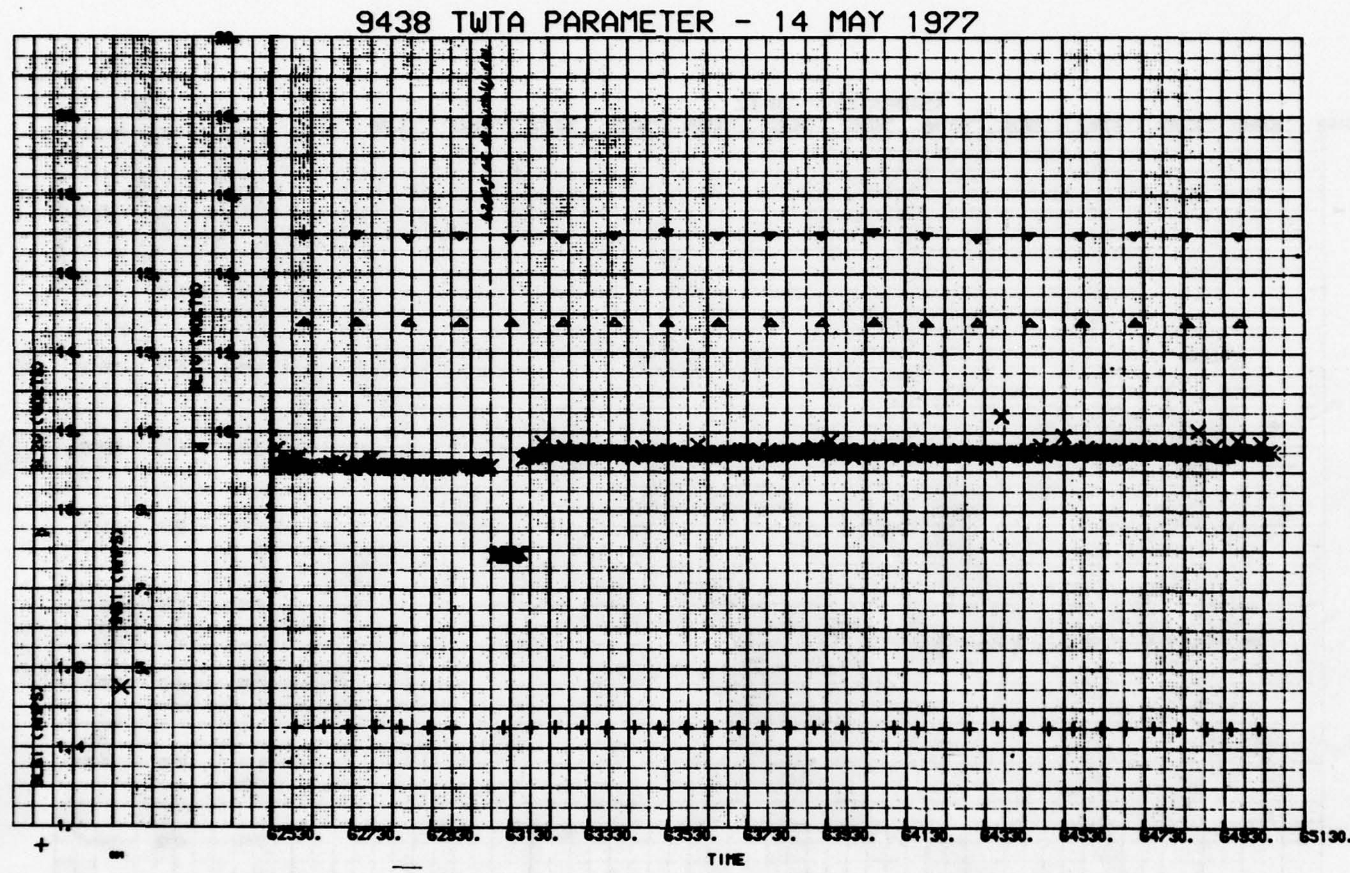

Figure 3.1-3. F8 HLTWTA-1 Initial Orbit Turn On Data Shows Nominal Operation of High Voltage Timer Followed by Successful Application of High Voltages to TWT

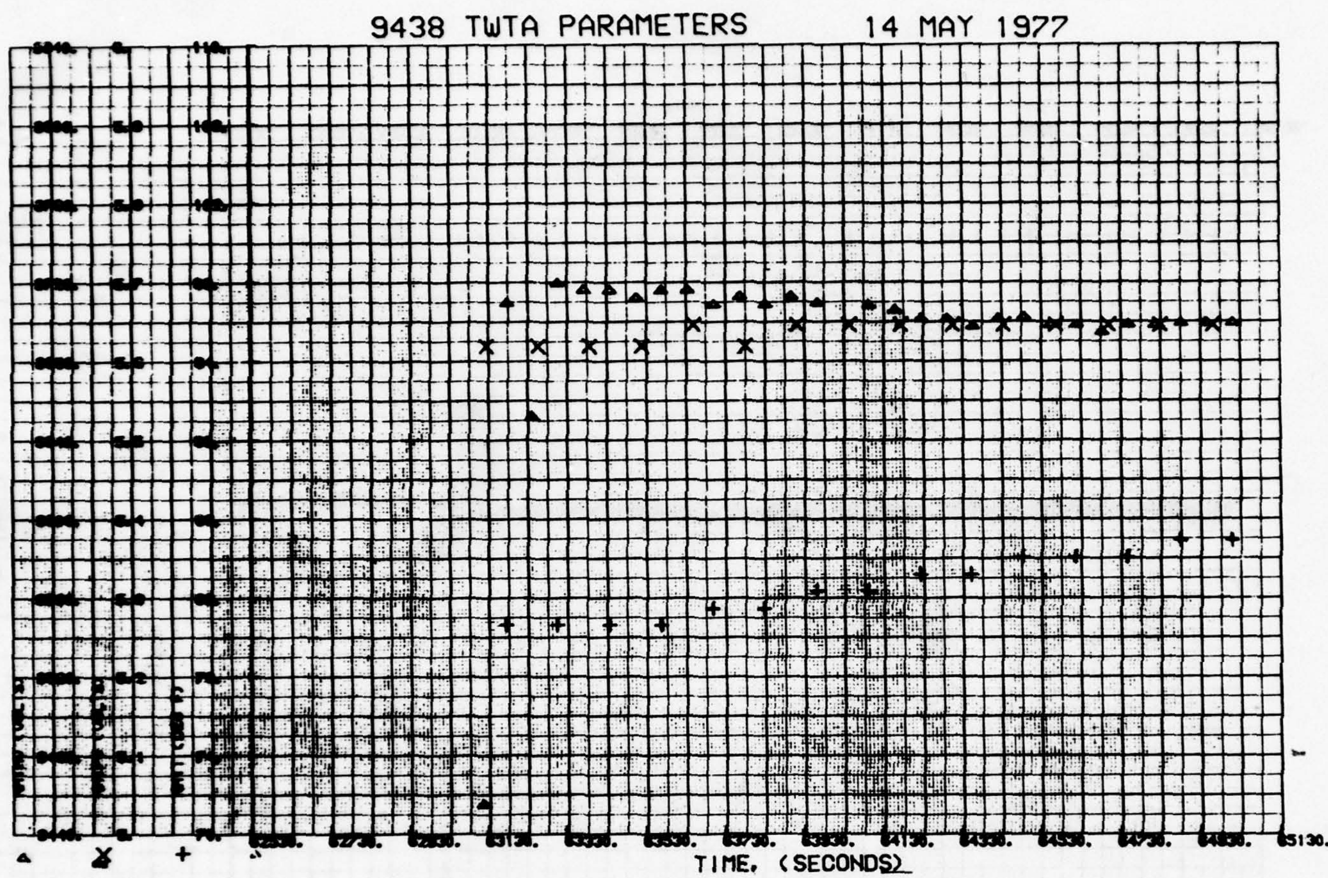

Figure 3.1-3. F8 HLTWTA-1 Initial Orbit Turn On Data Shows Nominal Operation of High Voltage Timer Followed by Successful Application of High Voltages to TWT (Continued)

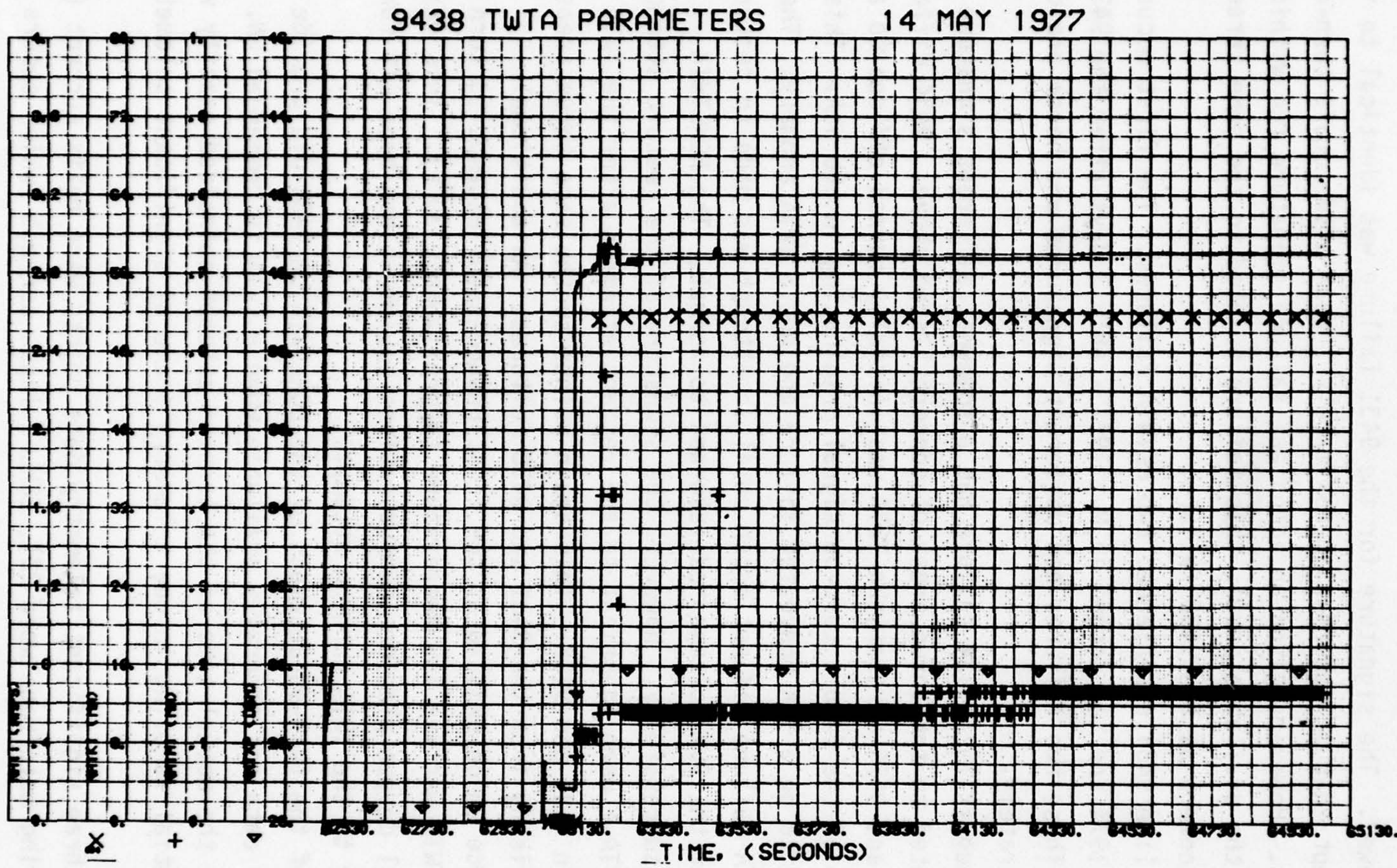

Figure 3.1-3. F8 HLTWTA-1 Initial Orbit Turn On Data Shows Nominal Operation of High Voltage Timer Followed by Successful Application of High Voltages to TWT (Continued)

voltage portion of the power supply, the helix overcurrent trip circuit, and the TWT itself. Since the 20 May 1977 9438 HLTWTA failure was the third on the 777 program, the previous 9431 and 9434 TWTA failures were also reviewed. The signature for the 9431 failure was identical to the 9438, except that it occurred approximately 1 year after orbit turn-on, not 6 days. However, given an identical failure signature (to within the limits of the available data), this failure pointed to the same three areas of concern as the 9438 failure.

Satellite 9434 experienced two HLTWTA failures. The first occurred in August 1974 and the second in May 1977 - only 3 days after the 9438 failure. These two failures had different signatures and hence are considered separately.

The August 1974 9434 failure had a somewhat different signature but still pointed to the three areas of concern listed above. 9434 differed from 9431 and 9438 in that the TWTA was initially turned off due to a drop in voltage of the 5-volt turn-on signal originating in the SLA. This was determined to be a SLA converter failure and not a TWTA anomaly. The actual TWTA failure did not occur until an attempt was made to restart the TWTAs after the SLA voltage had returned to normal. The NCHLTWTA restarted successfully. However, the signature of the restart attempts for ECHLTWTA-1 were identical to the restart attempts after the TWTA failures on 9431 and 9438. This again points to the same three areas of concern arising from the 9431 and 9438 failures. An additional circumstance which existed at the first unsuccessful attempt to turn on the 9434 TWTA was its low temperature (approximately 30^{o}F). This existed because all despun platform communications equipment had been off for some time prior to the TWTA turn-on attempt.

One of the turn-on attempts of the ECHLTWTA on 9434 did provide some additional data not generally available when a TWTA is commanded ON. In this case, the actual time of the turn-on attempt coincided exactly with the sequential sampling in one telemetry frame of significant telemetry bits.

The three significant telemetry data points were helix current (which occurs during mainframe word 22), ECHL 1 input current (which occurs during mainframe word 23), and main bus current (which occurs during mainframe word 28). Helix current and main bus current are both subcommutated

words sent every eighth frame, while input current is a mainframe word sent approximately once per second. It is important to note that all three telemetry data points occurred during the same telemetry frame, time tagged at 63,481 seconds after GMT 8/17/74. The telemetry bit rate is 250 bps, the word length is 8 bits, and the frame length is 32 words. Thus, the time interval between sampling helix current and TWTA input current is 32 ms, the time interval between sampling input current and main bus current is 5 x 32 = 160 ms, and the frame length is slightly greater than 1 second. The helix current read nine counts or approximately 0.07 mA; some 32 ms later, the TWTA input current read 2.78 amperes, and the main bus current which was sampled 160 ms after input current showed an increase of 2.55 amperes from the previous sample of about 8 seconds before. The next sample of input current approximately 1 second later went to 0 counts on the next frame, helix current went to 0 counts at the next sample occurring approximately 8 seconds later, and main bus current decreased by 2.79 amperes the next time it was sampled approximately 8 seconds later.

The helix current value of 0.07 mA is somewhat low for the drive condition existing at this time, which consisted of beacon drive only, resulting in a TWTA output at least 10 dB below saturated power output. Spacecraft calibration data showed that helix current ranges from 0.26 mA at 10 dB below saturation to greater than 0.8 mA at 2 dB below saturation. However, it appeared that the helix current reading was valid and not due to spurious noise or interference. This is substantiated by the fact that the input current indicated by the TWTA input current sampled 32 ms later was 2.78 amperes and the increase in main bus current 192 ms after the helix current reading indicated an increase of 2.55 amperes. The difference between input and main bus current increase is due to the current drawn by the TWTA when the heater only is on, which is about 0.3 ampere. Thus, the total main bus increase, including an increase of 0.3 ampere occurring immediately after the TWTA ON command, is 2.55 + 0.3 or 2.85 amperes, which corresponds closely to the observed input current value of 2.78 amperes. It should be noted that the main bus current decreased by 2.79 amperes 8 seconds after the TWTA indicated turn-on, and stabilized at the original value of 2.85 amperes less than the value read at time 63,481 two samples later at time 63,499 seconds.

The TWTA input current normally has a surge at turn-on which settles to within less than 1 ampere above steady state within 10 ms. Based on this fact and the discussion of the previous paragraph, the following conclusions can be drawn:

- Helix current probably was sampled almost immediately after high-voltage turn-on and is a valid reading.
- ECHL-1 input current sampled 32 ms after helix current is a steady-state value since this value is substantiated by the main bus current reading occurring 160 ms later. This current is low compared to a normal reading of 3.2 amperes for this TWTA.

Conclusions that can be drawn from the data are as follows:

a) TWTA operation during time-out of the high-voltage cycle is normal.

b) Since normal time-out of high voltage requires the presence of +5 volts, it is highly improbable that the TWTA turn-off was caused by a sudden interruption of this function occurring exactly at the time of high-voltage turn-on. Further, the TWTA failed to turn on again the next day using converter No. 2 instead of No. 1.

c) The TWTA internal fault circuit caused the TWTA to turn off after a brief period of high voltage which lasted for less than 1 second. It should be noted that the time constant of the fault circuit is 0.3 second, which is consistent with the observed data.

The above conclusions again point to the same three areas for investigation identified above.

The May 1977 NCHLTWTA failure on 9434 occurred suddenly, with no previous sign of degradation, just as the other 777 orbit TWTA failures. However, when attempts were made to restart the failed TWTA, no response at all was observed on any of the TWTA telemetry measurements. Verification that the satellite received and processed the turn-on command was possible by observing a decrease in main bus current upon receipt of the command. This is caused by turning off the THA heaters, a function which is performed as part of executing a HLTWTA ON command. Since there was no

response to two attempts to restart the failed TWTA, several additional areas of investigation had to be considered. These include:

a) Command implementation circuitry in the SLA which supplied the +5 Vdc turn-on signal to the HLTWTA

b) The fuses in the TWTA primary power lines

c) The start regulator and main regulator in the TWTA power supply.

3.2 ORBITAL TWTA TURN-ON DATA

An additional body of data was reviewed to attempt to further narrow the areas of concern identified by the actual failure data. This was the successful turn-on data for all the TWTAs on 9437 and 9438. A comparison of the successful turn-on signatures could possibly indicate something significantly different about the failed TWTA. Examination of the telemetry data during turn-on did show some differences, primarily in the shape of the knee of the input current curve at the application of high voltage to the TWT. Turn-on characteristics for 9438 ECHLTWTA-1 and 9437 NCTWTA-1 are shown in Figures 3.2-1 and 3.2-2. The remaining curves are in Appendix A.

No judgments could be made which would enable elimination of any of the above items strictly from the orbit data. These have to wait a failure modes analysis and an evaluation of the relative likelihood of candidate failure modes. In fact, it appeared that NCHLTWTA-1 on 9438 had more transients on the knee of its input current curve than the other TWTAs on the 9438 or the four on the 9437. However, several other TWTAs have some pulses on the knees of these input current curves. No additional insight into the possible failure mode was gained from these data.

3.3 GROUND TEST DATA

Although the 9438 TWTA failure appeared to occur without warning, there were transients on the input current at application of high voltage in orbit, which was not what would be normally expected. Therefore, a study was performed of the ground test data for all eight HLTWTAs in payload 4 (9437 and 9438 satellites) to see if there was an historical difference in this characteristic for the failed TWTA. This study included review of all steady-state operating data as well as ground test turn-on data.

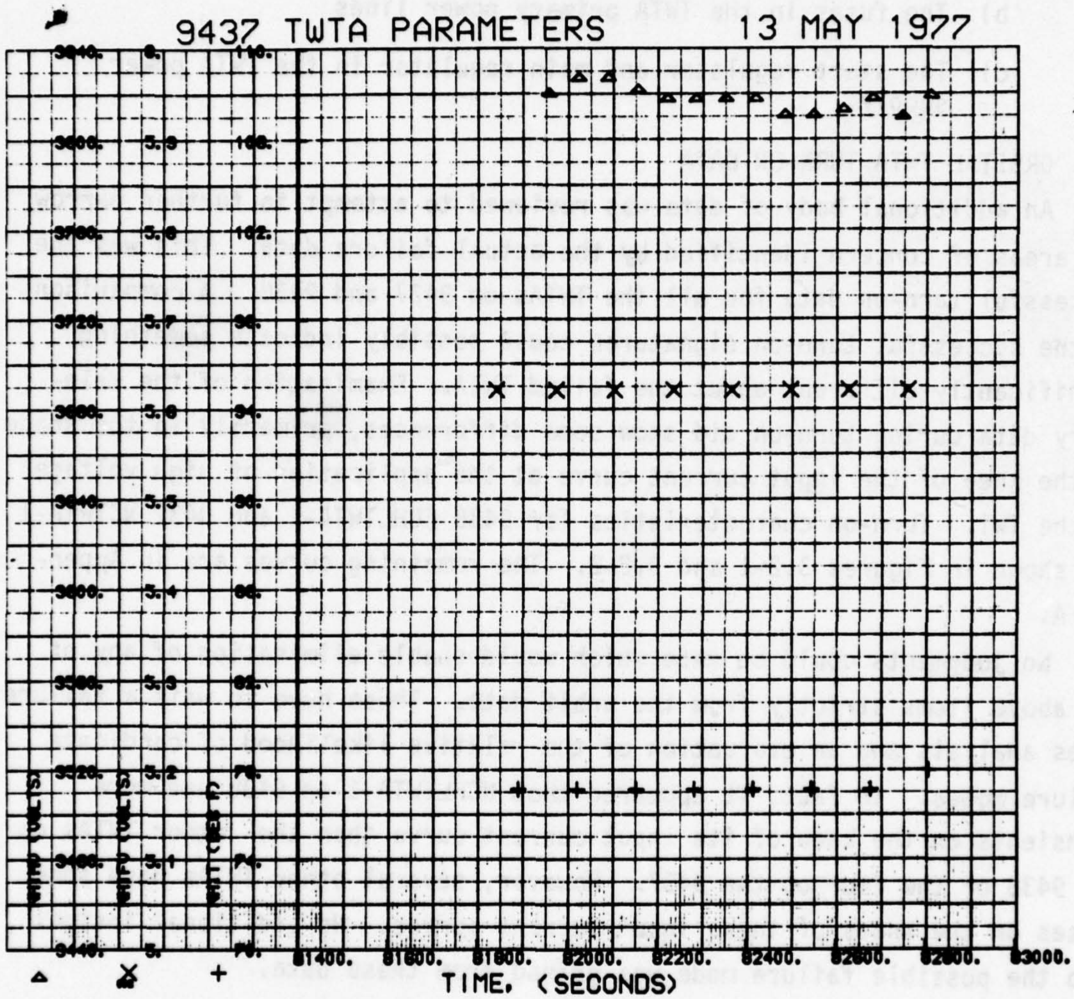

Figure 3.2-1. F7 NCHLTWTA-1 Turn On Characteristics Show Some Input Current Transients Upon Application of High Voltage

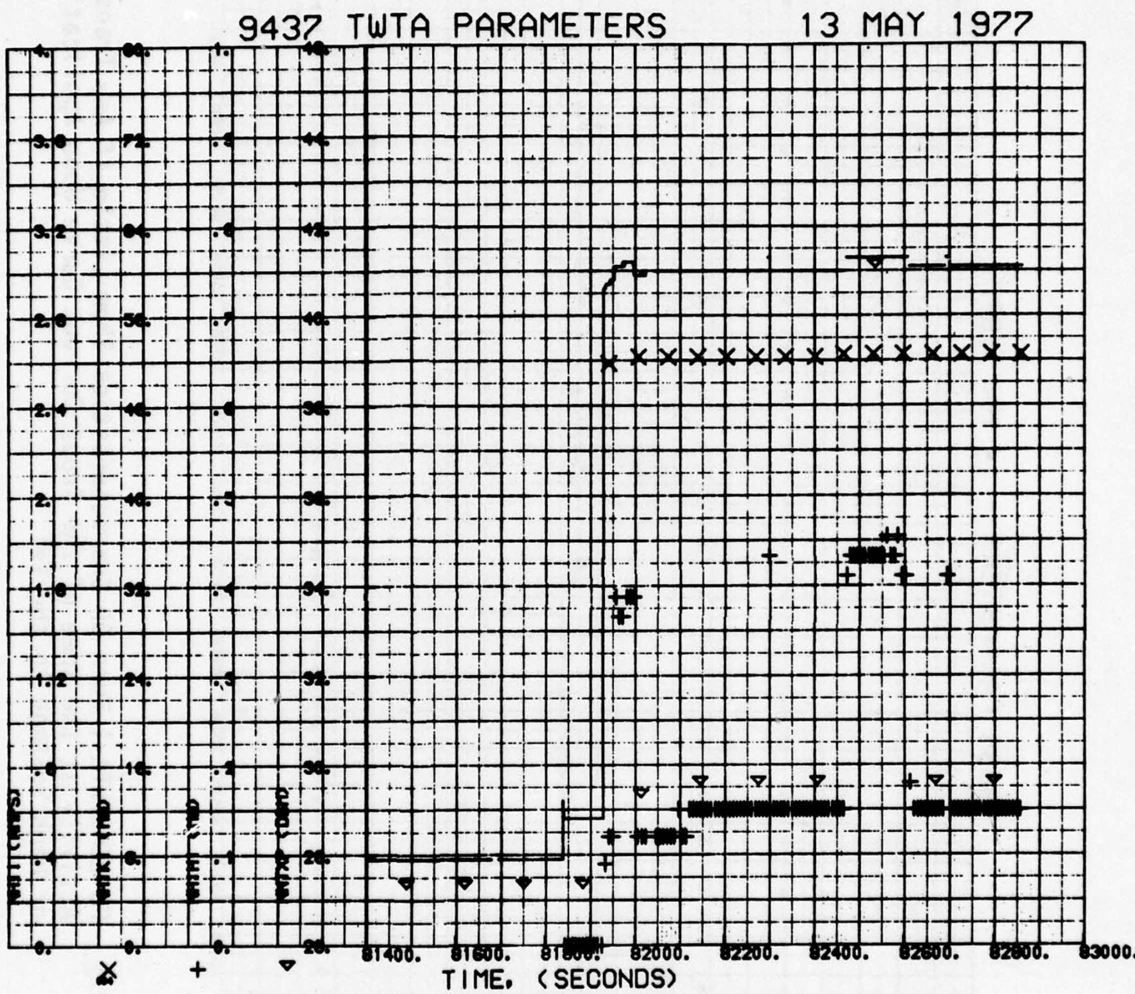

Figure 3.2-1. F7 NCHLTWTA-1 Turn On Characteristics Show Some Current Transients Upon Application of High Voltage (Continued)

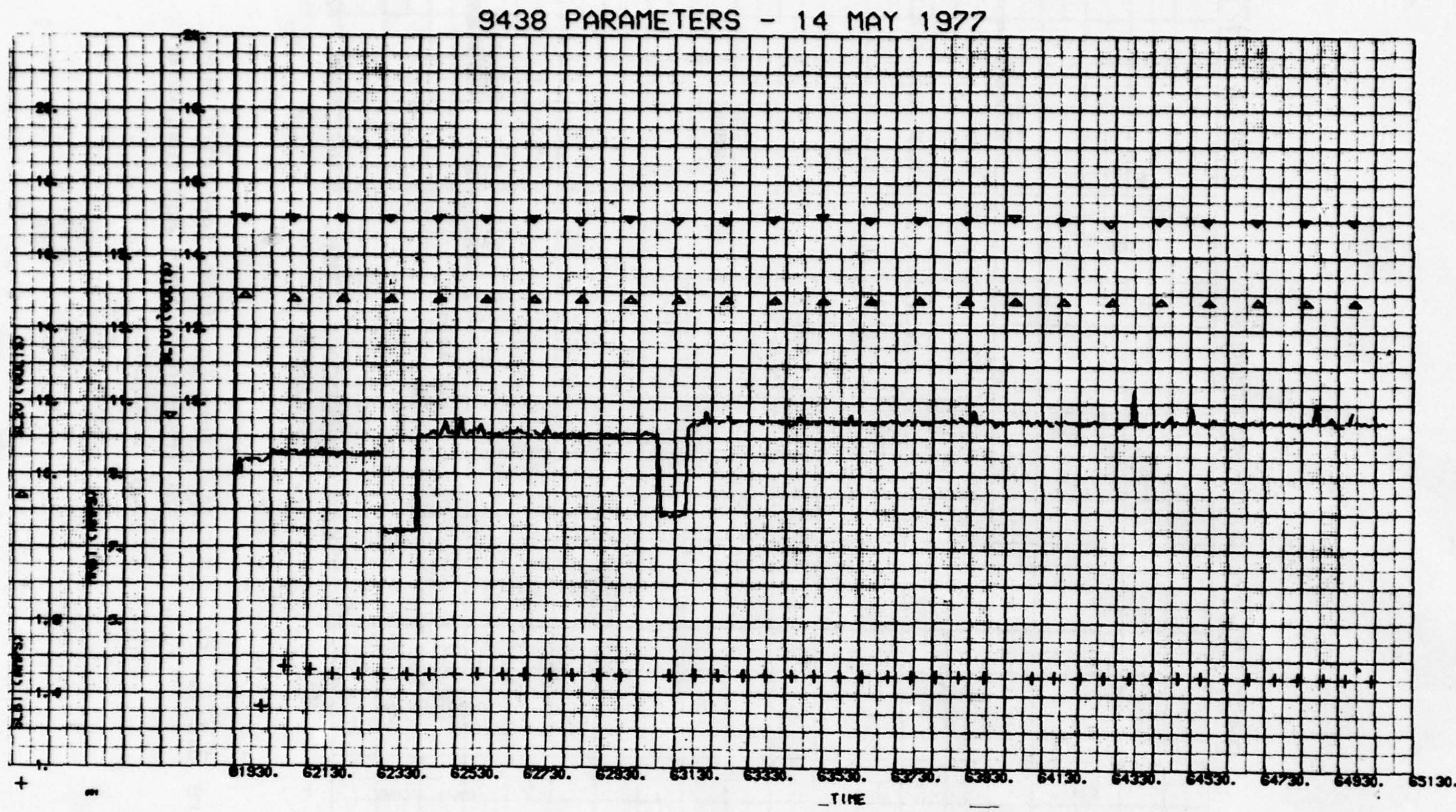

Figure 3.2-2. F8 ECHLTWTA-1 Turn On Characteristics Show Little if Any Transients Activity at the Knee of the Input Current Curve Upon Application of High Voltage to the TWT

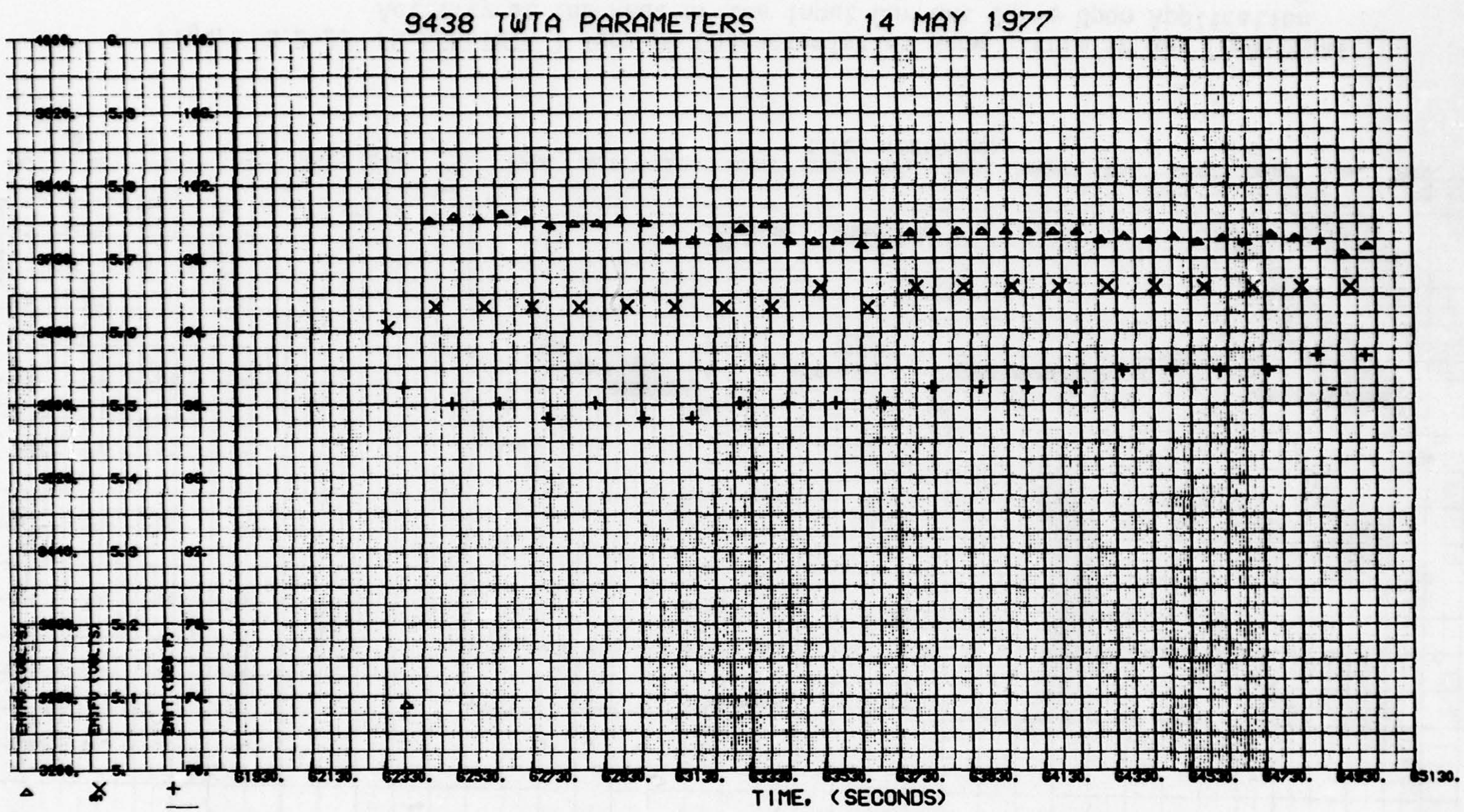

Figure 3.2-2. F8 ECHLTWTA-1 Turn On Characteristics Show Little if Any Transients Activity at the Knee of the Input Current Curve Upon Application of High Voltage to the TWT (Continued)

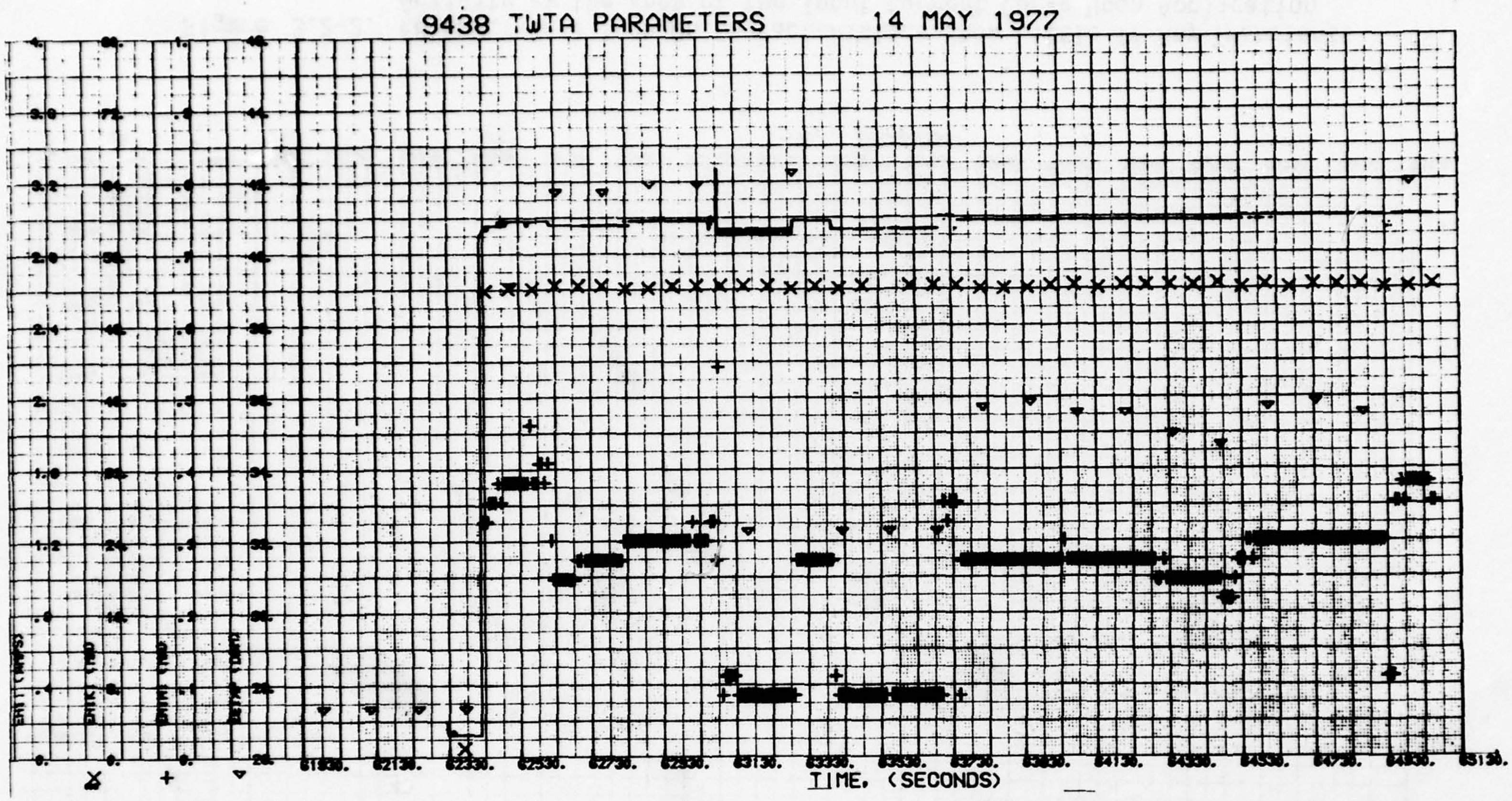

Figure 3.2-2. F8 ECHLTWTA-1 Turn On Characteristics Show Little if Any Transients Activity at the Knee of the Input Current Curve Upon Application of High Voltage to the TWT (Continued)

3.3.1 Ground Test Turn-On Data

Computer plots of digital telemetry data for TWTA input current and helix current were made for each TWTA turn-on event during satellite thermal vacuum (TV Phase 1) test, integrated system test (IST 2), and the system test performed at ETR prior to launch.

The degree of variation in input current at turn-on, as shown in the plots (Figures 3.3-1 through 3.3-4), varied considerably from amplifier to amplifier. Although F8 seemed to have more variability than the others, there were still other TWTAs which had some variability (9437 ECHLTWTA-1), for example) which appeared occasionally. The results of this data review were studies by contractor and subcontractor engineers, and no positive relationship to internal problems could be established. There was some feeling that the input current transients observed in S/N 24-17 could have been indicative of a discharge phenomenon occurring in the amplifier at initial turn-on. However, this could not be established conclusively. It was agreed that gathering of data from additional TWTAs would be useful for future study.

3.3.2 Ground Test Operating Data

The operating data for all eight HLTWTAs in 9437 and 9438 were reviewed together to determine whether there was anything which might distinguish S/N 24-17 from the other seven amplifiers. Basically, there did not appear to be anything of such a nature. The failed amplifier had nominal gain and its telemetry parameters fell within nominal bounds. In addition, the telemetry parameters were steady and did not exhibit any drift over a period of approximately 770 operating hours between amplifier assembly and launch. Of these 770 hours, approximately 400 had been accumulated while installed on F8, of which 92 were in a vacuum. Summaries of these operating data are tabulated in Tables 3.3-1 and 3.3-2. Additional data on the remaining 9437 and 9438 HLTWTAs are contained in Appendix A.

Two items of data concerning input and cathode current required some investigation before it could be concluded that there was no ground test anomaly for this amplifier. The input current, as reduced from the telemetry voltage and calibration curves, consistently was recorded at 2.6 to 2.7 amperes at 33 volts or 3.4 amperes at 28 volts during unit test. This corresponded to a unit power consumption between 89 and 95 watts. At

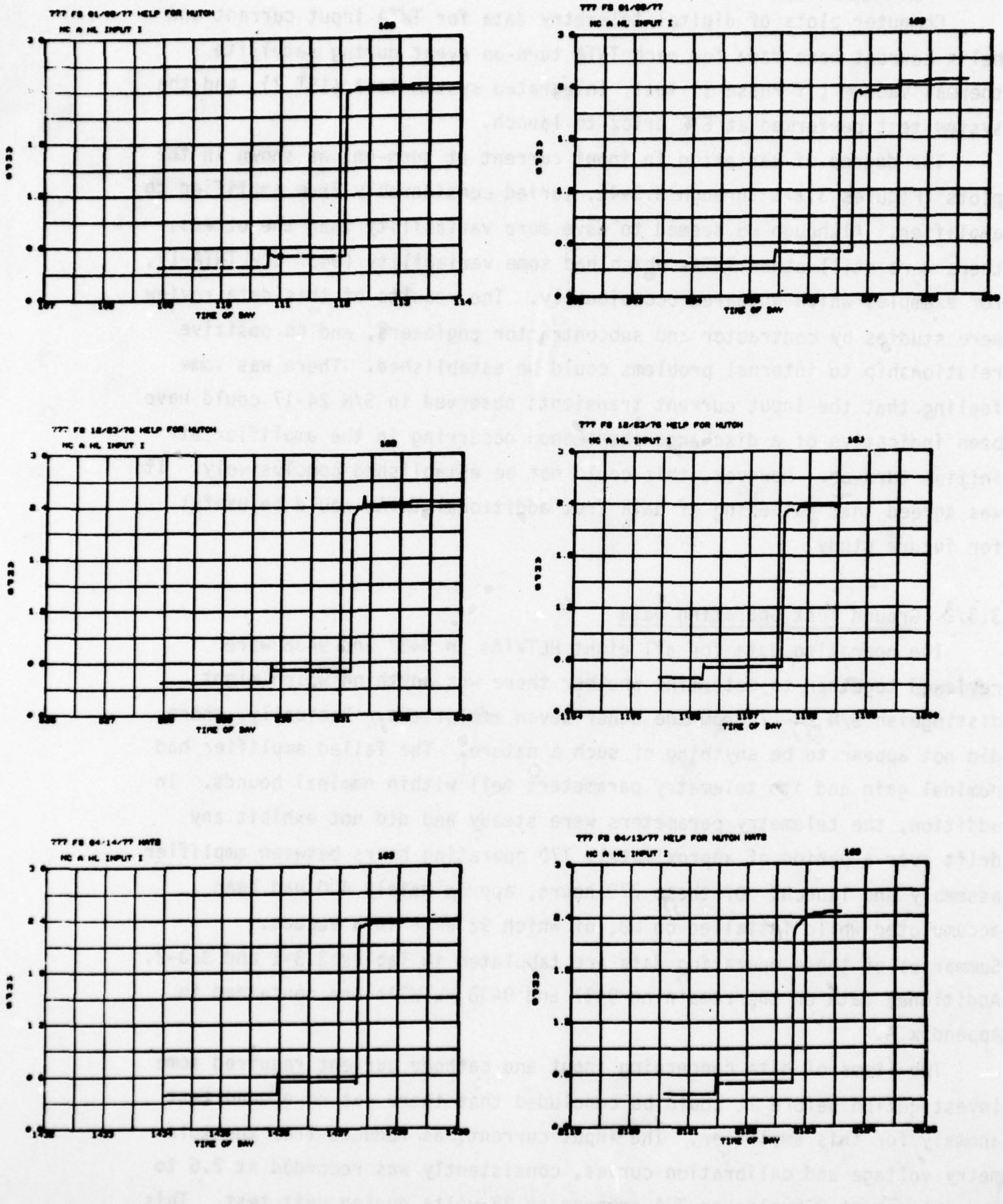

Figure 3.3-1. F8 NCHLTWTA-1 Input Current Turn On Characteristics Show Intermittent Transient Activity During Some Turn On Events

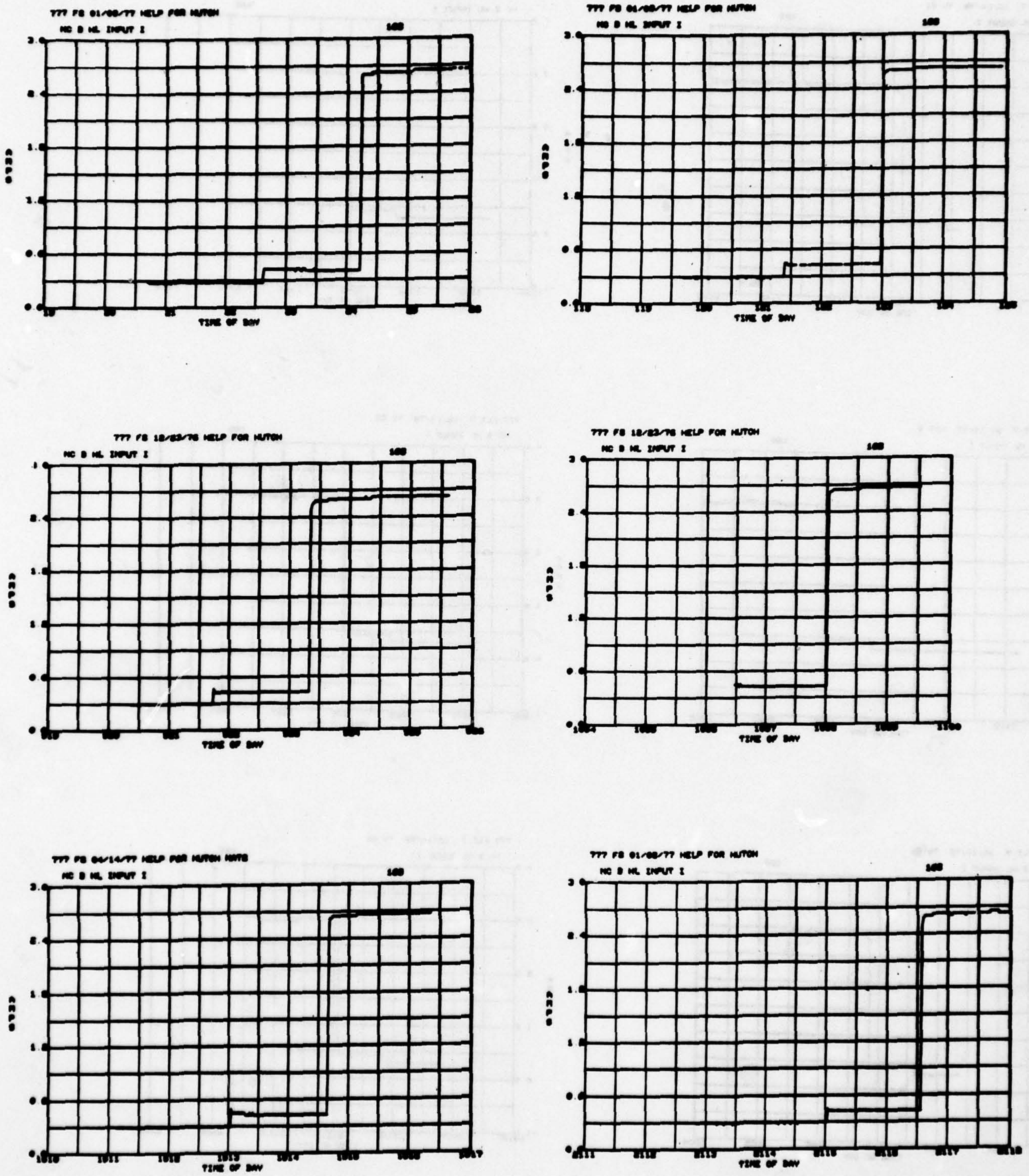

Figure 3.3-2. F8 NCHLTWTA-2 Input Current Turn On Characteristics Show Little Variation Between Successive Test Startups

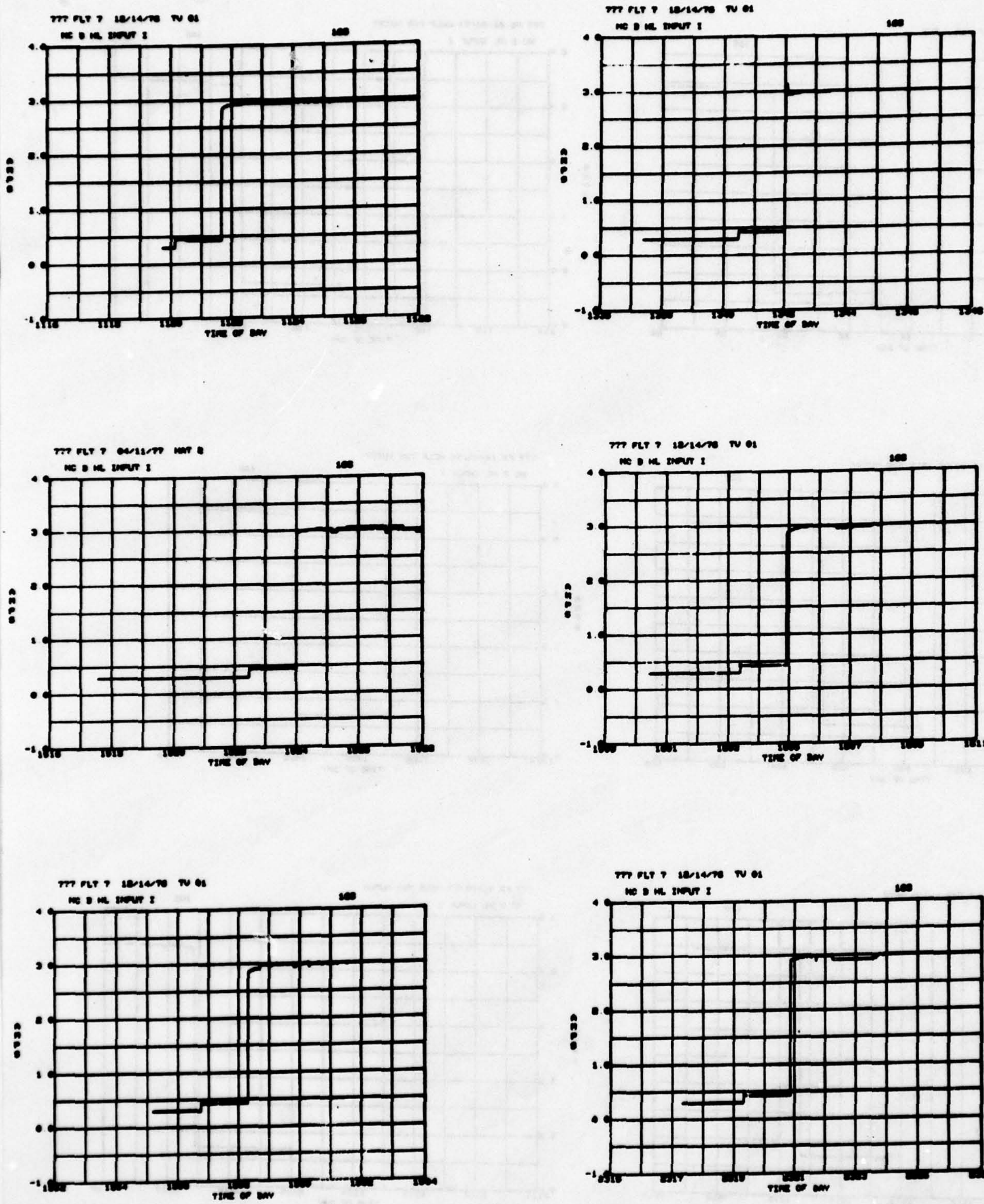

Figure 3.3-3. F7 NCHLTWTA-2 Input Current Characteristics Show Some Variation in Transient Content Between Successive Starts

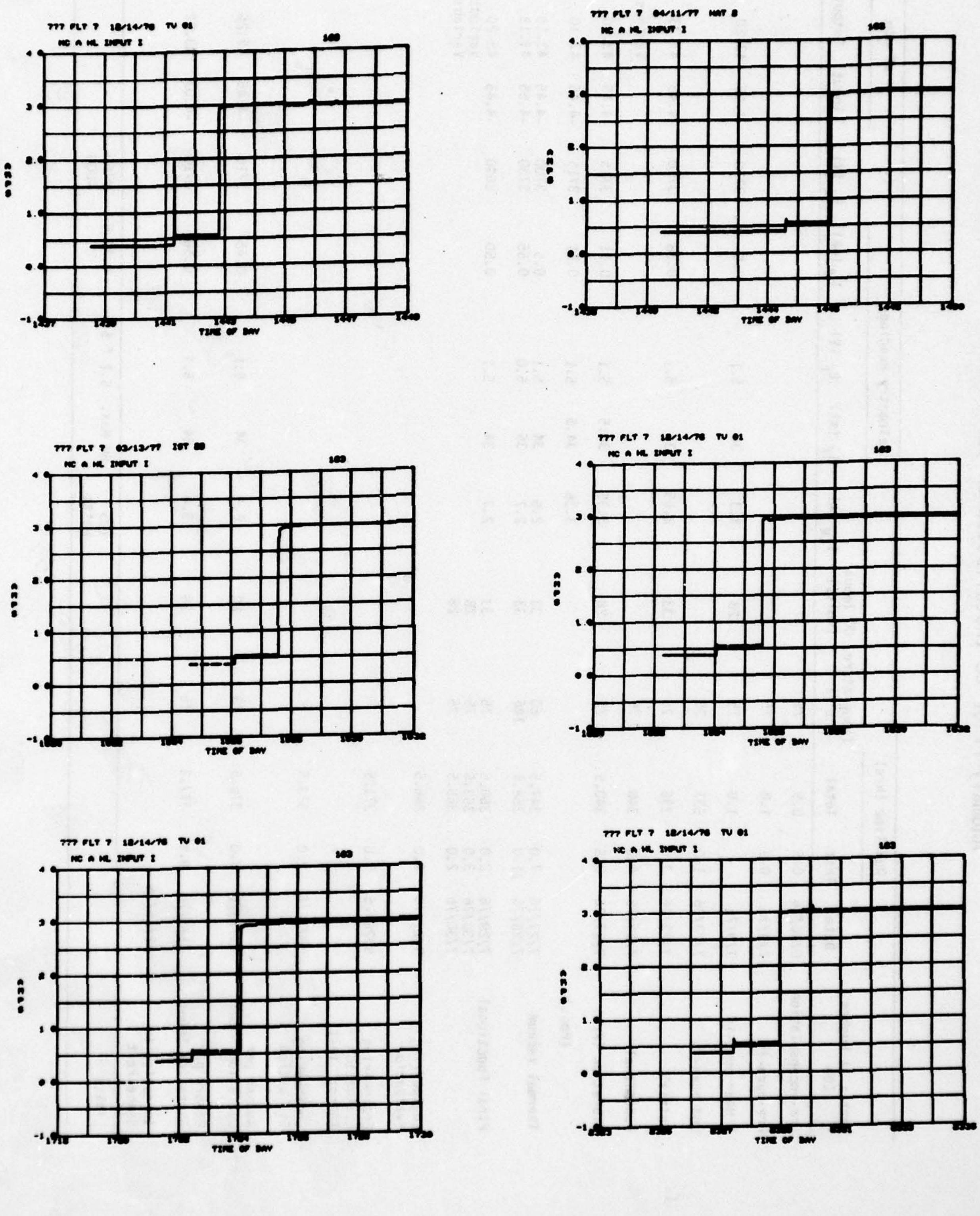

Figure 3.3-4. F7 NCHLTWTA-1 Input Current Characteristics Show Little Variation Between Successive Starts

Table 3.3-1. NCHLTWTA S/N 24-17 Does Not Show Any Ground Test Operating Anomaly Prior to Installation on Satellite 8

		Run Time (hrs)				Telemetry Readings					RF dBm	
Test = at Hughes EDD	Date	Test	Total	Temperature (^oF)	DC Input (volts)	I_{IN} (A)	I_K (mA)	E_F (V)	I_W (mA)	E_K (V)	Input	Output
Pre-encapsulation	6/16/76	0.5	0.5	75								
Pre-burn-in	7/9/76	0.5	1.0	75								
0 Hour burn-in	7/9/76	-	1.0	75	28	3.3	34	5.1	0.5	3710	-4.45	43.20
End burn-in	7/23/76	1.0	333	75								
Initial	7/23/76	3.0	336	75	33	2.65	34	5.1	0.38	3710	-4.45	43.23
Functional	7/26/76	4.0	340	75								Various
Vibration (Pre)	7/27/76	0.5	340.5	75	28	3.35	34.5	5.1	0.51	3715	-4.45	43.30
(Post)						3.36	34.5	5.1	0.51	3715	-4.45	43.10
Thermal Vacuum	7/27/76 7/28/76	7.0 11.0	347.5 358.5	60 146	33 33	2.6 2.7	34 35	5.1 5.0	0.5 0.55	3700 3730	-4.45 -4.65	43.18 43.18
Final Functional	7/29/76 7/30/76 7/30/76	2.0 3.0 2.0	360.5 363.5 365.5	75 75 75	33 28 28	2.7	34	5.1	0.50	3690	-4.45	43.20 Various Various
Engineering Evaluation	9/27/76	1.0	366.5									
Engineering Evaluation - Thermal Test	9/28/76	5.0	371.5									
Engineering Evaluation	10/7/76	2.0	373.5									
Rework per Operation Sheet	11/1/76	3.0	376.5	75	28	3.4	34	5.1	0.45	3710	-4.45	43.26
Rework per Operation Sheet	11/3/76	0.8	377.3	75	28	3.4	34	5.1	0.50	3710	-4.03	43.22
Installed in Spacecraft "	11/16/76											
Limits						105 Watts	60 Max.	5.2 " 5.6	0.22-5	3760-4000	-	-

Table 3.3-2. NCHLTWTA S/N 24-17 Does Not Show Any Ground Test Operating Anomaly After Installation on Satellite 8

Test = at Hughes EDD	Date	Run Time (hrs) Test	Total	Temperature (°F)	DC Input (volts)	Telemetry Readings I_{IN} (A)	I_K (mA)	E_F (V)	I_W (mA)	E_K (V)	RF dBm Input	Output
CPT No. 1	11/20/76	6.3		91.8	≈31.5	2.61	50.47	5.67	0.56	3801		40.2
SSTT (Hot) (Cold)				102 55.1	≈31.5	2.64 2.80	52.6 49.7	5.51 5.62	1.15 0.3	38.46 3831		40.08 41.6
IST No. 2	12/23/76	7.8	473.0	96	≈31.5	2.98	51.6	5.67	0.50	3762		40.28
IST No. 3	1/6/77 1/7/77	9.2 7.4		94	≈31.5	2.98	51.6	5.64	0.50	3777		40.07
TV EQ	1/8/77	26.2		80	≈31.5	2.79	51.6	5.64	0.47	3781		40.21
TV WS	1/11/77 1/12/77	10.8 19.2		93	≈31.5	2.98	51.6	5.67	0.50	3758		40.21
IST No. 4	1/13/77	3.1		95	≈31.5	2.98	52	5.64	0.50	3766		40.07
TV EQ	1/16/77	55.6		71	≈31.5	3.0	51.6	5.64	0.84	3803		-
TV WS	1/18/77		631.3	95	≈31.5	2.88	51.6	5.64	0.83	3644		-
CPT No. 2	1/24/77 2/16/77	9.3	 668.9	84	≈31.5	2.93	51.6	5.64	0.45	3788		40.07
IST No. 23	3/15/77	15.1		86.6	≈31.5	2.93	51.5	5.61	0.47	3818		39.8
HIST 1	3/23/77 3/25/77	26.2	765.9	96.6	≈31.5	2.98	51.5	5.64	0.47	3770		39.64
HIST 2	4/14/77 5/4/77	3.2	 769.1	99	≈31.5	2.98	51.6	5.67	0.50	3770		39.50
Limits					2.5 - 4.5	43-57	5.29-5.92	0-3.2	3540 - 4060			42.0 dBm ±2

system tests, the input current was read at 2.88 to 2.98 amperes at 31.5 volts, corresponding to a power input of about 90 to 93 watts. A review of the calibration procedure and test equipment used by the vendor disclosed that a parallel external load was attached to the TWTA input current telemetry output which did not exist on the satellite. This load of 50 k ohms had the effect that for a given true input current the telemetry voltage with the load would be less than without. Hence, for a given telemetry voltage, a larger current would be deduced from the calibration curves when the load was removed. Such was the case here.

The second discrepancy noted between unit and system data is the recorded value for cathode current during unit tests. It is consistently recorded at 34 mA, not approximately 50 to 52 as seen during system test. This discrepancy was also related to a telemetry calibration problem.

4. FAILURE MODES AND EFFECTS

4. FAILURE MODES AND EFFECTS

As discussed in earlier sections of this report, it was concluded that the F8 HLTWTA failure appeared to be in the high-voltage sections of the TWT power supply or in the TWT itself. This general conclusion was also consistent with the earlier failure on 9431 and 9434. It also was not inconsistent with the conclusions reached during the investigations subsequent to an orbit failure of another military program's HLTWTA which had similar characteristics. Both HLTWTAs were identical in high-voltage design. An analysis and failure simulation test program was initiated as part of this anomaly investigation to attempt to localize the failure cause to a particular component or area of the TWT and its power supply.

4.1 FAILURE MODE AND EFFECTS ANALYSIS

A review of the Failure Modes and Effects Analysis (FMEA) of the HLTWTA identifies many piece-part failures which would result in zero TWTA output. This number exceeds 400, excluding solder connections, parasitic paths, interconnect, or dielectric breakdown paths. The candidates can quickly be narrowed when these failure modes are viewed against the signature of the orbit failure, i.e., the unit operated normally during heater warm-up and tripped off upon high-voltage turn-on. In addition, the signature was reported to have no RF output pulse during attempted high voltage turn-on and resultant turn-off. There has been some discussion about whether an RF pulse could have been detected, although reports of the sensitivity of the ground station measurement equipment indicate such detection was possible and was to be expected if an RF signal were present. These data were important in attempting to bound the number of possible failure modes.

With the supplemental information of the signature, the most likely candidate is a "high-voltage related" failure mode. This could be a piece part, interconnect, or dielectric material in the high-voltage path of the power supply or TWT.

A number of possible failure modes were identified from review of the TWTA FMEA which could have a signature similar to the orbit failures. Selected ones of these were tested using a breadboard of the TWT power supply with a HLTWT as a dynamic load. These tests were performed at room

temperature and normal atmospheric pressure. A summary of the failure modes so derived appears in Table 4.1-1. The table includes the failure mechanism, its effects on TWT operation, and an assignment of the degree of likelihood of the listed item. It should be noted that there are a number of failure modes which cause the TWTAs to shut off and/or not be restartable. A summary of failure modes reviewed during this test program is given in Table 4.1-2.

A number of individually tested failure modes exhibited failure signatures similar to the F8 failure - with one exception. When an attempt was made to restart the TWTA with the failure intact, a "burst" of RF energy would be noted at high-voltage turn-on before the TWTA shut itself off. Also, the telemetry values would hold at excessive values for approximately 1 second after application of high voltages. In the case of 9438, several orbit turn-on attempts were conducted in conjunction with an appropriate ground station specifically to look for such a "burst" of RF signal. None was detected. The TWTA input current is measured every 1.024 seconds on the satellite, and in the 11 attempts to turn on the failed TWTA, no indication of high input current was found in the telemetry data. This consideration cannot be extrapolated to F1 and F4 since no similar turn-on attempts were conducted, and the TWTA input current was sampled only every 8 seconds on F1 through F6 satellites.

4.2 HIGH-VOLTAGE STABILITY ANALYSIS

In addition to the classical failure analysis which considers part failures, short circuits, etc., consideration was given to possible instability or marginal stability in the high-voltage regulation loop as the cause of one or more of the 777 failures.

The aggregate of several variable parameters, which in most cases are not well controlled, has caused this type of problem in some TWTAs. The individual parameters are: Power supply source impedance, TWT dynamic characteristics during defocus, heater emission changes with life, and the voltage margin between TWT defocus and the nominal operating cathode voltage level.

Table 4.1-1. Selected Failure Modes and Effect Analysis. (Failure modes involving collector shorts to ground are judged most likely cause of orbit failures. Others cannot be totally ruled out but are judged less likely.)

	Possible Failure Mechanism	Failure Mechanism	Failure Effect/Signature	Failure Probability Evaluation and Reason Why	Comments/Remarks
1.	High-voltage filter capacitors (C_3, C_4, C_7, C_2, C_5)	Short	Correct signature EPC unable to provide high voltage to tube, shutoff after 90 seconds time out	LOW: 5 and 6 kV rated mica capacitors, application of approximately 2.5 and 3.8 K respectively. Review of dissected samples shows no design weakness.	Failure would be due to mechanical stress as opposed to electrical stress. Part not encapsulated.
2.	Cathode and associated leads	Open	Not correct failure signature	VERY LOW: Breadboard testing could verify correct failure signature for the short failure mode.	
		Short to ground	Correct failure signature		
3.	Collector and associated leads	Open	Not correct failure signature	N/A	Burst of RF energy at attempted turn-on, not detected in orbit attempts.
		Short to ground	Correct failure signature	Medium	Shorted collector to ground occurred on S/N 14-15 in thermal vacuum tests.
4.	Output connector/ coaxial cable failure	Open	Not correct signature	VERY LOW: TWT designed such that unit not degraded by open or shorted output connector so unit would be responsive to nominal ON commands. Problem would tend to be more sensitive to only a narrow temperature band	
		Short	Not correct signature		
5.	T1 transformer (collector transformer)	Open winding	Correct signature	Very low	Design and process review showed no reason to suspect these parts. Dissected samples showed excellent processing and parts.
		Potting/encapsulant beakdown (inter-winding short) primary to secondary breakdown	Correct signature	Very low	
6.	T2 transformer (cathode transformer)	Open winding	Correct signature	Very low	See above for T1 transformer.
		Potting/encapsulant breakdown (inter-winding short)	Correct signature		

Table 4.1-1. Selected Failure Modes and Effect Analysis (Continued). (Failure modes involving collector shorts to ground are judged most likely cause of orbit failures. Others cannot be totally ruled out but are judged less likely.)

	Possible Failure Mechanism	Failure Mechanism	Failure Effect/Signature	Failure Probability Evaluation and Reason Why	Comments/Remarks
7.	T3 transormer ("collector" current TLM)	Short circuit (interwinding)	Not correct signature	N/A	
		Primary winding open	Not correct signature	N/A	
		Primary to secondary short	Correct signature	Very low	See above for T1 transformer
8.	Open feedback string (cathode voltage to regulator) (open R4, R5, R7 in HV module; R4, R27 in SC module)	Open	Not correct signature	N/A	Burst of RF energy at attempted turn-on, not detected in orbit attempts
9.	Shorted diode bridge (Z1 through Z9)	Short	Signature depends on which bridge fails	Very low	Bridge has two series elements in each leg. Telemetry values held excessive for .1 second should have been seen during F8 turn-on attempts.
		Open	Not correct signature	N/A	Increase output ripple slightly but would not cause shutdown
10.	Inductors in cathode voltage output of power supply	Open	Not correct signature	N/A	
		Short	Not correct signature	N/A	
11.	VR2 drift to 40 mA leakage (trip circuit reference)	Aging and drift	Cause trip circuit to operate at nominal levels	Very low	Review to date shows no component drift
12.	Helix configuration	Helix to pin welding	Helix intercepts beam, high-current, trip off	Very low	
		Helix insulation	Not correct signature	N/A	
13.	RF overdrive of TWTA	External/internal high-level RF source overdrives TWTA	Not correct signature	N/A	

Table 4.1-1. Selected Failure Modes and Effect Analysis (Continued). (Failure modes involving collector shorts to ground are judged most likely cause of orbit failures. Others cannot be totally ruled out but are judged less likely.)

Possible Failure Mechanism	Failure Mechanism	Failure Effect/Signature	Failure Probability Evaluation and Reason Why	Comments/Remarks
14. High-voltage ARC in power supply	Dielectric failure (aging and thermal cycling)	Correct signature	Low	
	Failure at a discontinuity (repair after rework)	Correct signature	Low	6 kV high-potential test performed after rework
	Failure from outgassing of entrapped voids	Correct signature	Low	Vacuum impregnated potting process used
15. Short near CR 12 in high-voltage module	Short recurred or T2 overstress	Correct signature	F8 only - medium. All others - very low	No specific applicable corrective action taken except to replace CR 12. Not likely failure mode.
16. Worst-case I_W turn-on and/or instability	I_W trip at turn-on attempt, dynamic characteristic of TWT shift with life	Correct signature	Low	Review of data packages shows wide divergence of TWT characteristics. No test evidence of TWT turn-off due to changing I_W characteristics.
17. High voltage ARC in TWT				
Cathode to ground	ARC across BeO insulator between cathode to ground	Correct signature (see Item 2)	Very low	
Collector to ground	Short (ARC) across BeO insulator between collector and TWT baseplate	Correct signature	Medium	Two test failures observed: 1) S/N 14-15 during extended thermal vacuum temperture cycle test 2) S/N 22-3 during initial thermal vacuum test prior to use as life test TWTA

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9438 HIGH LEVEL TRAVELING WAVE TUBE AMPLIFIER ANOMALY. VOLUME I--ETC(U)

AUG 78 J A DURSCHINGER F04701-75-C-0257

UNCLASSIFIED TRW-28600-AR-015-01-VOL-1 SAMSO-TR-77-184-VOL-1 NL

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Table 4.1-2. Summary of Breadboard Failure Simulation Results (Only the shorted cathode or shorted collector to ground failure modes simulated the 9438 orbit failure.)

	Simulated Failure Mode	Test Results
1.	Short cathode to chassis	Unit shut down, on restart heater timed out and unit shut off, no RF
2.	Open cathode or cathode leads	Not like orbit failure signatures
3.	Short collector lead to chassis	Unit shut down, on restart heater timed out and unit shut off, no RF
4.	Open feedback resistor string	Unit shut down, on restart heater timed out, unit shut off, burst of RF energy output
5.	Shorted CR 12 on cathode voltage telemetry	Unit shut down, on restart heater timed out, unit shut off after about 1 second of excessive telemetry readings
6.	Shorted high-voltage rectifier	Unit shut down, on restart heater timed out, unit shut off after about 1 second of excessive telemetry readings
7.	Shorted cathode to helix (chassis ground)	Same as (1) above
8.	Shorted collector to helix (chassis ground)	Same as (3) above
9.	Open collector	Large burst of RF output at time out just prior to input overcurrent trip shutting unit off
10.	Simulated arcing cathode through various resistors to chassis ground	Not like orbit failure signatures
11.	Open anode or anode leads	After heater time out, high voltage came on and remained on but telemetry measurements indicated low values
12.	Shorted anode or anode leads	After heater time out, high voltage came on and remained on with telemetry measurements on slightly lower than normal, including RF output

It was determined that several cycles of sustained high-voltage oscillation would, on the negative swing of voltage, raise helix current above the nominal dc trip level and cause shutdown of the TWTA. The following rationale was used to evaluate this potential failure mode.

The team has found a plausible explanation for the relatively short life (100 hour) failure of the 9438 TWTA (S/N 24-17). The remaining three 777 failures had long operating life in the relatively benign environment of space and therefore could be drift related. The most logical area to look for such a characteristic would be heater emission, which has a designed-in wear-out characteristic.

The theory that life degradation of TWT emission and/or component changes in the semiconductor module cause marginal phase margin or sustained oscillation of the control loop was pursued by:

a) Review of TWT dynamic characteristic (cathode activity) in the data packages

b) Review of cathode and collector source impedance (data package)

c) Analyses of the resonant frequencies for second-order power filters

d) Review of test data, especially during turn-on transients

e) Review of qual unit control-loop test data

f) Breadboard testing.

Cathode activity curves are recorded in the data package before, during, and after 750-hour burn-in at the TWT level. In addition, a test is conducted at the TWTA level. There is a wide divergence between TWTs of both the slope of helix current rise and the presence of sine wave perturbation during the space charge-limited transition. Although these tests are not equitable to operating conditions, where emission is saturated and E_K is the variable, it seems that they indicate the way a particular TWT geometry defocuses.

A sharply defocusing TWT would result in an abrupt transfer of beam current from collector to helix. This type of dynamic load change would

shock a marginal control loop into oscillatory modes, with possible high-voltage excursion. Two tests which indicate source impedance are included in the data package:

1) Each high-voltage power supply is tested with a fixed-input of 19 volts and resistive loads. During this test, helix current is increased from 0 to 5 mA in small steps. Cathode voltage is recorded at each step. The change in cathode voltage varied between power supplies from 50 to 175 volts and seemed to be a function of ringing voltage spikes on the high-voltage transformer secondary windings. With very light loads on the helix, the filter would peak charge to the ringing positive value. As load is applied, this spike is integrated to the peak value of the square-wave voltage. The major part of the voltage change occurred in the first mA of helix current.

2) The second test involves measuring the drift of collector voltage with warm-up time. This test is not formal, and acceptable limits are determined by the test engineer. The typical procedure, as recorded in the data package, is to replace the power switching transistors of the high-voltage inverter if drift is considered excessive.

   The collector voltage drift is probably due to a change in high-voltage transformer secondary winding ringing caused by switching characteristic changes in the power switching transistors during warm-up. The most likely parameter in the transistor would be storage-time difference and the attendant overlap of on-time.

   It is difficult to predict the significance of this drift, but it would appear it is self-degenerating. As collector voltage decreases with spike amplitude increases (unbalance of power switching transistors), the depression ratio is changing to increase helix current, tending to normalize the effect.

An analysis of the resonant frequencies of the power filters was done to identify the most likely frequency of oscillation. This is approximately 400 Hz. Resonant peaking of the power line filter would occur at approximately 1100 Hz. Resonant frequency of the high-voltage filter is approximately 200 Hz.

The qualification unit control-loop tests are limited to audio input at specified levels, with acceptance limits set by TWTA output RF quality. Unfortunately, this test gives no indication of margin in control-loop design. However, peaking was noted at 400 and 1100 Hz, as indicated above.

Interpretation of hard-wire telemetry test data is complicated by:

a) Some telemetry outputs are nonlinear during transients.

b) Most output telemetry circuits have large capacitors for noise suppression and are slow to respond.

c) Unless operating at high tape rates, the recorder is too slow to identify transient waveshapes.

d) Some recordings of TWTA telemetry outputs indicate sustained low-level oscillation when running at high rates. At slow rate, the oscillations are converged into a solid line. No determination has been made as to whether this is a recorder noise problem (60 Hz) or actual TWTA control loop instability.

Despite the above, differences between TWTAs during the turn-on transient can be seen. High helix current with respect to cathode voltage varies, and in some units a transient overshoot of cathode voltage occurs. It is felt that a TWTA which focuses close to the nominal cathode voltage operating level is most susceptible to oscillation.

The high-speed tape taken during high-voltage turn-on (S/N 14-15) and after the "hard" failure of the collector insulation showed high excursions and sine wave signals on several telemetry outputs. The frequency of these waveforms was approximately 400 Hz. During this transient, which lasted for approximately two cycles, the feedback voltage had to be low. For this reason it is difficult to attach any significance to this, other than that under overload condition, some form of end-limited oscillation occurs in the chopper amplifier at the resonant frequency of the chopper filter network.

Breadboard testing was relocated to low priority and was not performed at this writing; however, the following tests were suggested:

a) Gain frequency plots and phase margin measurements.

b) To simulate degradation of emission, reduce heater power in steps and test TWTA dynamic response. Monitor with an oscilloscope EK transient waveforms at turn-on and RF drive charges.

c) Remove capacitor from helix circuit and measure helix current waveshape relative to E_k during turn-on, temperature change, and heater power variation.

4.3 HELIX AND INPUT CURRENT PROTECTION ANALYSIS

Three of four 777 TWTA failures in space have operated this circuitry either at shutdown or during subsequent restart attempts. For this reason,

the circuit was suspected as a possible failure mechanism. The circuitry illustrated in Figure 4.3-1 was analyzed in detail, with the following conclusions:

a) All circuit components, with the exception of VR2, were eliminated as possibilities based on the unlikely probability that a modestly rated part would fail in three different TWTAs.

b) VR2 establishes the reference voltage level to which helix and input current sense signals are compared. A drift in this zener could increase sensitivity to a point where initial calibration levels would shut down the TWTA. This would be even more critical at high-voltage turn-on where inrush transients for both sensed signals are high.

VR2 is especially suspected because it is applied in the circuit at a zener level of 3.1 volts and 50 μA. The part is a 1N751A with a manufacturer's nominal rating of 5.1 volts and 20 mA. As had been done on at least two previous occasions, an extensive review of the part (1N751A) was conducted with no positive results. Although the part is misapplied, there is no reason to expect that it will not function adequately in the circuit.

Leakage drift with time is low compared with levels required to affect TWTA performance. Testing, date code search, manufacturer's history, and part analysis were used to support this conclusion. In addition, it seems likely that the condition would have been found during ground testing. Helix and input current signals are integrated in a common capacitor through rectifiers to develop the trip signal level. During normal operation, input current establishes the sensed voltage level and the helix rectifier is reverse biased.

The input current is sensed in the power lines and varies as a function of input voltage (constant power). At low-line conditions, the sensed signal approaches 50 percent of the calibrated trip level. The combination of low line and temperature extremes should have shown a drift problem during testing.

The transient and static characteristics of the helix and input current sensors were examined with the following results:

a) Input current is sensed with a magnetic amplifier. The saturated output is very close to the calibrated trip setting (approximately 8.5 amperes) limited by the peak value of the square wave voltage exciting it. The ac square wave is derived from an inverter operating on the 19 volt bus and varies in amplitude proportional to 19 volt bus voltage. The minimum 19 volt bus voltage for operation of the current trip circuit is approximately 15 Vdc. Below this value, the magnetic amplifier

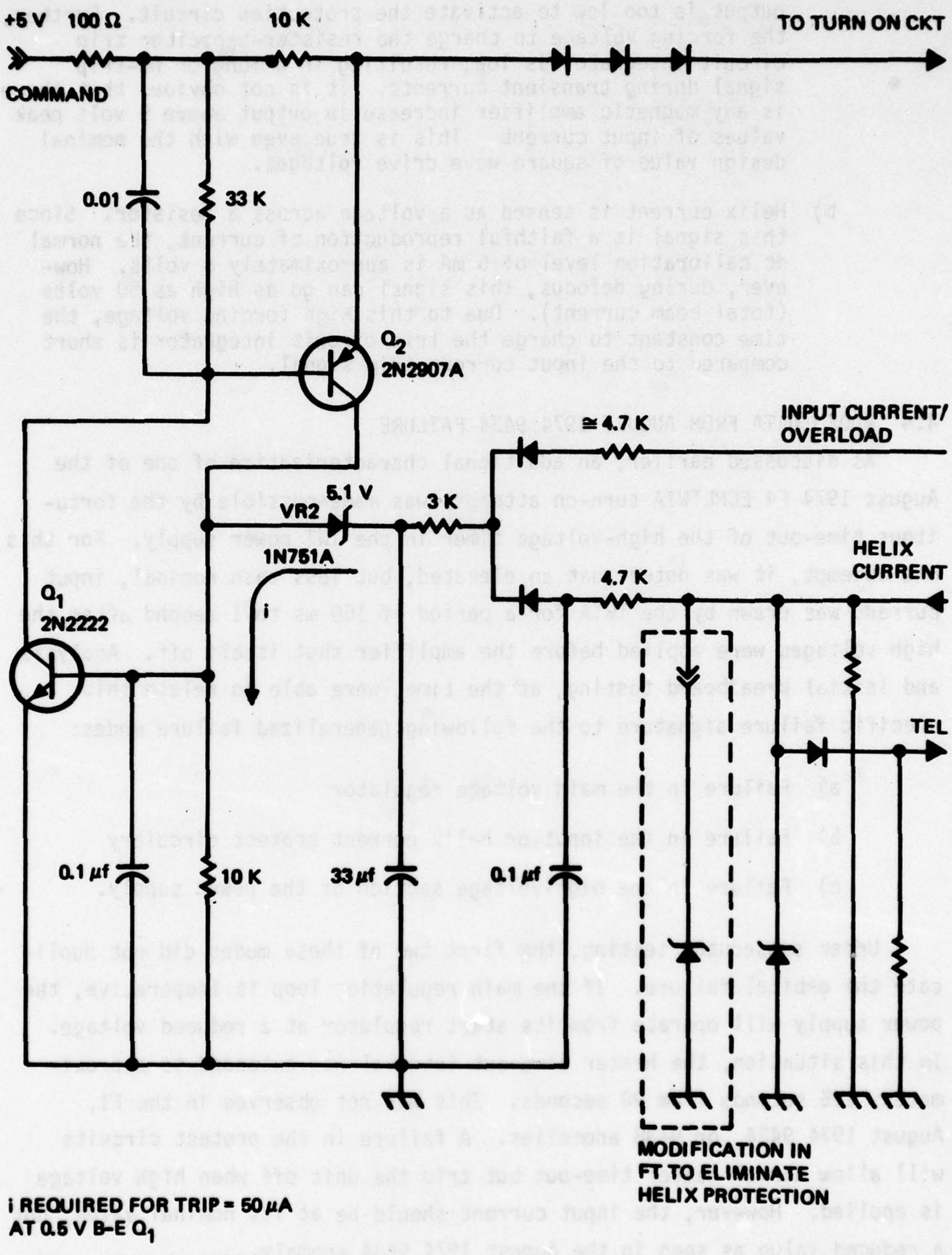


Figure 4.3-1. Helix Overcurrent Trip Circuit Schematic. The reference diode (VR2) although misapplied has shown no evidence in test or ground usage of shifting characters to cause the trip level to change.

output is too low to activate the protection circuit. Further, the forcing voltage to charge the resistor-capacitor trip circuit integrator is low, resulting in a long or no-trip signal during transient currents. It is not obvious that there is any magnetic amplifier increase in output above 9 volt peak values of input current. This is true even with the nominal design value of square wave drive voltages.

b) Helix current is sensed as a voltage across a resistor. Since this signal is a faithful reproductfon of current, the normal dc calibration level of 6 mA is approximately 6 volts. However, during defocus, this signal can go as high as 50 volts (total beam current). Due to this high forcing voltage, the time constant to charge the trip circuit integrator is short compared to the input current trip signal.

4.4 ADDED DATA FROM AUGUST 1974 9434 FAILURE

As discussed earlier, an additional characterization of one of the August 1974 F4 ECHLTWTA turn-on attempts was made possible by the fortuitous time-out of the high-voltage timer in the TWT power supply. For this one attempt, it was noted that an elevated, but less than nominal, input current was drawn by the TWTA for a period of 160 ms to 1 second after the high voltages were applied before the amplffier shut itself off. Analysis and initial breadboard testing, at the time, were able to relate this specific failure signature to the following generalized failure modes:

a) Failure in the main voltage regulator

b) Failure in the input or helix current protect circuitry

c) Failure in the high-voltage section of the power supply.

Under subsequent testing, the first two of these modes did not duplicate the orbital failure. If the main regulation loop is inoperative, the power supply will operate from its start regulator at a reduced voltage. In this situation, the heater time-out interval was extended to approximately 125 seconds from 90 seconds. This was not observed in the F1, August 1974 9434, or 9438 anomalies. A failure in the protect circuits will allow normal heater time-out but trip the unit off when high voltage is applied. However, the input current should be at its nominal value, not a reduced value as seen in the August 1974 9434 anomaly.

The third failure mode, when reviewed analytically, did not contradict the August 1974 F4 anomaly signature.

Several failures in the high-voltage section could have caused low dc bus current and high helix current. Failures might be open or shorted high-voltage secondaries of transformer T1 or bridge rectifier shorts Z1, 2, 3, 4, or 5. The high dc resistance of these windings, when shorted, limits the increase of 19-volt bus current to a moderate amount. A net decrease of input current could result due to the reduced acceleration potential of the cathode and the resultant collector current decrease.

These failures unbalance the collector helix voltage or remove anode voltage. Under most of these operating conditions, it seems reasonable that helix current would increase to the trip level.

The August 1974 9438 ECHLTWTA failure was first evidenced by an inability to restart the amplifier after it had been exposed to two non-nominal operating conditions:

1) The +5 Vdc command voltage had fluctuated and eventually decreased to 0 volts, thus turning both the EC and NC TWTAs off.

2) The despun platform became cold after the TWTAs were turned off, so the restart attempt was conducted when the TWTAs were about 20 to 30°F.

It should be noted that NCHLTWTA restarted successfully after exposure to the identical conditions. Because of these specific orbit conditions, a series of tests was devised and conducted under room temperature and ambient pressure conditions to characterize the nature of responses by the HLTWTA to abnormal disturbances in its power and control lines.

These tests, reported in detail in Appendix B, disclosed that at low command voltages the TWTA was more susceptible to power-line transients than when the command voltage was at the upper end of its range. Also, it was observed that a HLTWTA power supply could oscillate when the voltage was somewhat less than the nominal value.

The remaining test did determine certain main bus interruption conditions which could cause unbalanced conditions in the power supply, possible excessive helix current, and TWT dynamic oscillation. This type of condition could have the effect of turning a good amplifier off using the helix overcurrent trip circuit.

5. REVIEW MANUFACTURING AND TEST DATA PACKAGES AND PAST TEST FAILURES

5. REVIEW OF MANUFACTURING AND TEST DATA PACKAGES AND PAST TEST FAILURES

The review of data packages and past test failures had as its primary objective one of obtaining an improved understanding of the types of failures which had occurred in the past during all phases of ground operation. This understanding could assist in selecting the most probable cause of the various 777 orbit TWTA failures, particularly if the ground history showed any consistency with orbit failure history. Both the review of data packages and test failures did disclose information related specifically to the F8 failure and to all 777 TWTA orbit failures in general.

5.1 REVIEW OF DATA PACKAGES

A comprehensive review was made of the manufacturing and acceptance test data packages for the HLTWTAs on F7 and F8 and for all the remaining HLTWTAs available for F9 through F12. The review served a dual purpose: (1) to see if there were any clues in these data which could shed light on the 9438 failure and (2) to ensure there were not any test or manufacturing failures which required additional explanation or understanding before the affected amplifier could be considered of flight quality. A secondary objective of this review was to obtain an overall understanding of what method or methods were used by personnel at the vendor in troubleshooting anomalies and conducting failure investigations. This review also allowed an evaluation that the TWTAs, as delivered, would operate properly for their intended life. The most striking finding concerned the HLTWTA which failed on Satellite 9438 (S/N 24-17).

The history, summarized in Table 5.1-1, shows the high-voltage module (S/N 002) had an intermittent short. The fault was traced (by lifting leads) to the area of CR12, which is half of a telemetry output rectifier on one winding of HV XFMR T2. CR12 was replaced and the fault cleared. CR12 was not checked outside to confirm the failure. CR12 is a Unitrode JANTXV IN 4942, LDC 7433. An intermittent short of this part is highly unlikely. It is considered reasonable to believe the short is in the board or wiring, not the diode, and has recurred on orbit. In any case, the fault could have damaged T2 during ground testing, and it is possible T2 failed later in orbit.

Table 5.1-1. Chronology of High-Voltage Module S/N 002. (CR12 Replaced to Correct High Current Drawn During Module Testing was not a Verified Fault)

Date	S/C Module S/N	HV Module S/N	Activity
2/7 to 2/17/76		002	Replaced all diode bridges (defective lot)
3/8/76		002	Successful test on HV module tester
3/9 - 3/10	002	002	Integration of HV and semiconductor modules, found E_b drift
3/11 - 3/23		002	Evaluation, replaced T-1 (collector transformer), drew excessive current during test on HV module tester
3/24/76		002	Wire checked, no anomalies, successful functional test on HV module tester
3/25/76	002	002	Reintegrated HV and semiconductor modules, drift in E_b still present
3/25/76		002	Substituted collector filter capacitors external to unit, drift stopped
3/29/76		002	Reworked HV module to replace collector filter capacitors
4/2/76*	002	005	Found E_b drift during integration testing
4/15/76	004	005	Successfully tested, no E_b drift
4/13/76	005	002	Semiconductor module appeared to fail during integration testing.

*Eb drift concluded to be attributed to S/N Module 002, eventually traced to mismatch of switching times of Q5 and Q6.

Table 5.1-1. Chronology of High-Voltage Module S/N 002. (CR12 Replaced to Correct High Current Drawn During Module Testing was not a Verified Fault) (Continued)

Date	S/C Module S/N	HV Module S/N	Activity
4/14/76		002	Tested in vacuum chamber OK
4/14/76	022	002	During integration testing drew excessive current, tripped
4/17/76		002	HV module tested separately and drew excessive current
4/20/76**		002	Found "shorted" CR12 and replaced, unit retested on module test successfully
5/4 - 5/5/76	006	002	Successfully integrated semiconductor module 006 and HV module 002.
5/13/76	006	002	Unit potted

** Assumed excessive current attributed to "shorted" CR12. Diode not tested after removal so could not be located in 1977.

A breadboard simulation test was performed in which CR12 was shorted. The resultant signature had the same characteristic as the failure of S/N 24-17 in orbit. However, when the amplifier was restarted with this type of fault, the high voltage, input current, and helix current telemetry measurements stayed at excessive amounts for approximately 1 second.

Since the sampling interval of TWTA input current is 1 second, it would seem reasonable that a high input current reading would have been observed on telemetry during one of the 11 S/N 24-17 turn-on attempts in orbit after the failure. Such was not the case, thus downgrading this possible failure source to the same level as the ones involving arcing of the collector, or drifting of the helix overcurrent trip circuit.

A total of 18 manufacturing data packages were reviewed and various comments noted on 12 of them. None of these seemed to relate directly to the previous orbit failure. A number did create a general feeling of dissatisfaction with the overall thoroughness employed by the vendor in troubleshooting and failure analysis.

There are a number of questions arising from repetitive problems and from peculiarities noted which, while not directly relatable to the orbit failures, should be answered:

a) High-Voltage Drift - There are several occurrences of high-voltage drift when semiconductor module and high voltage module are mated. The problem is cured by changing the Q5 and Q6 pair which drive the high-voltage transformers. However, it is not clear that end-of-life and worst-case conditions could not cause orbital problems.

b) Cathode Activity Change at TWTA Level - Almost all tubes show an apparent marked increase in cathode activity when mated to an electrical power converter. In many cases, the manufacturing data indicate that the filament voltage is above 5.6 volts, which would partly account for the effect. However, amplifiers 14-24 and 14-25 seem to show an increase in cathode activity test without high filament voltage. Two concerns thus arise:

   1) Should the filament voltage be set high when this is already said to be an exceptionally hot cathode?

   2) Does the change in cathode activity test indicate an undesirable rise in temperature for some other reason?

c) Small signal-gain variations and anomalies are frequent. Sometimes the amplifier is reworked (window cleaning, etc.); sometimes a waiver is requested. This parameter seems to act as a sensitive indicator for problems in the RF circuitry. It

appeared to the review team that closer attention and more consistency in diagnosing small signal-gain problems might be warranted.

d) In several cases, a wiring error or open wire was determined to be the cause of a test failure. In many of these instances, there did not appear to be any documented overstress analysis of the effects of the wiring error. This creates a definite concern.

A summary of the specific comments developed from this review is contained in the appendices.

5.2 PREVIOUS TEST FAILURES

A review was made of all previous test failures for all HLTWTAs produced for 777 (flight and life test units). A total of 47 failure reports were reviewed. A summary of the causes of failure for the 35 reports on the basic program and 12 on the replenishment program is shown in Table 5.2-1. Also, the failures which occurred during the 18-day thermal vacuum screening test are included in the table. The detailed reliability analysis reports are included in Appendix C. A number of the reported failures had some of the signature characteristics of the orbit failures (for example, spontaneous shutdown and/or inability to restart). However, generally an electrical or product design change was incorporated to remove the source of failure in the remaining TWTAs. It was also noted a significant number of early high-voltage failures existed in the TWTA power supply which were designed out in the early phases of the original 777 program.

Three reported failures occurred which warrant special mention. Two of these (occurring on TWTA S/N 011 and S/N 14-15) involved a high-voltage arc between the collector and TWT baseplate. The arc was at the collector insulating ceramic surface and its interface with the potting material which encloses the collector housing. The arc occurred in an area where apparently the potting material or conformal coating was not properly bonded to the ceramic insulator. The first failure was not extensively analyzed. The TWT was simply repotted and retested successfully. The second failure (S/N 14 to 15) did receive an extensive failure investigation reported in a separate section of this report. The existence of this confirmed ground test failure added weight to the probability that some, if not all, of the orbit failures were caused by improper bonding between the collector insulator and the surrounding potting compound or conformal coating.

Table 5.2-1. Summary of HLTWTA Ground Test Failure Experience Shows Two Instances of High-Voltage Arcing in the TWT Collector Assembly

Failure Cause	F1-6 and Life Test HLTWTAs	F7-12 HLTWTA	Special T/V Screening Test
TRW caused, waiver	2	0	0
Early high-voltage problems (designed out)	7	0	0
Workmanship	10	5	0
Test error	3	0	0
Part failure	2	1	0
Design change	5	0	0
RF connection	4	4	2
High voltage	1	0	1
Not resolved*	1[1]	2[2]	3[3]
Tests	35	12	6

*Not resolved:

1. Unit shutdown. Restarted. Tested 300 hours, no recurrence. TWT removed from TWTA and replaced.

2. a) Semiconductor module scrapped rather than isolated problem.

   b) Failure analysis in progress. Failure involved variations in small signal gain.

3. a) Intermittent shutdown. TWTA still under evaluation.

   b) Two cases: minor helix current transients under evaluation.

6. COMPONENT EVALUATION

6. COMPONENT EVALUATIONS

This phase of the investigation concentrated on the power supply section of the TWTA which contains the discrete component parts within the amplifier assembly. Parts were identified through failure modes analysis and testing which would cause the performance indications of the TWTAs failed in space. These were reviewed for test data, part history, failure experience, and applications. This review concluded that there were no identifiable part problems related to the known primary failure modes. The parts reviewed as a result of the failure analysis are given in Table 6-1.

Magnetics were reviewed for design and processing. Dissected samples of magnetics were inspected for voids or indication of poor bonding under the microscope. No design weaknesses were found. Processes and impregnation were excellent in the components reviewed. In addition, the data packages indicated no high-voltage problems in magnetics since the major high-voltage redesign of approximately 1970.

The most probable dielectric failure in magnetics would be in cathode transfer (B201627-002) or cathode current sense transformer (B201628-001). The failure would occur across the highest stressed dielectric which occurs between secondary and primary windings. In addition, physical spacing in this area is the most difficult to control. This failure would also give the correct TWTA failure signature. In general, open windings in high-voltage transformers and shorted turns in this type of construction are highly improbable. Had a design weakness been present, resulting in several TWTA failures, it surely would have shown up during testing.

Component failures which give the correct TWTA failure signatures are limited to high-voltage capacitors C_2, C_3, C_4, C_5, and C_7. Rectifier bridges Z_1 through Z_9, and helix current resistors R_1 (1.5K) and calibration resistor R_2 (SIT) (approximately 2250 ohms).

The high-voltage capacitors were studied extensively because they could account for all TWTA failures and are purchased as raw capacitors and encased and processed by Hughes. This type of capacitor has a history of very high reliability; however, it was thought possible that this unique application could cause mechanical stress that with time would result in failure to short. This review, which includes dissected samples, found no design weakness. It must be assumed this was not the cause of TWTA failures.

Table 6-1. Part Investigation Results Show There is No Identifiable Part Problem Related to the Primary Potential Failure Modes of HLTWTAs

Schematic Symbol	Part Type	HAC/EDD Part No.	Cause of Investigation	Results
CR12	Diode	JANTX1N4942 LDC 7433	Intermittent short in TWTA 24-17 high voltage module (S/N 002). Diode replaced, problem corrected. Diode lost and not analyzed.	Analysis of part construction and TRW history of similarly constructed diodes did not confirm a "short" failure mode.
C3, C4, C5	Capacitor, 0.01 μFd, 6 kV	B200379-012	Circuit analysis for possible short.	No history of prior part failure detected. Suspected failure mode not verified.
C2, C7	Capacitor, 0.01 μFd, 5 kV	B200379-011	Circuit analysis for possible short.	No history of prior part failure detected. Suspected failure mode not verified
VR2	Diode, zener	JANTXV1N751A LDC 7338	Circuit analysis of possible drift in reverse current could cause helix over-current trip.	Manufacturer, Motorola, supplied data of similar lot which showed good stability of reverse current. Also stated there were no problems with LDC 7338, i.e., results of Group A, B and screening tests were good and were normal. Motorola indicated that the reverse current leakage (I_R) measured at -2 to -3 volts would not exceed 5 μA during normal usage for the diode life. Suspected failure mode not verified.

Table 6-1. Part Investigation Results Show There is No Identifiable Part Problem Related to the Primary Potential Failure Modes of HLTWTAs (Continued)

Schematic Symbol	Part Type	HAC/EDD Part No.	Cause of Investigation	Results
T1, T3	Transformer	B201628-001	Circuit analysis of possible dielectric (primary to secondary) breakdown.	No part failure mode detected.
R6	Resistor, 10 k, 1/8 m		Same as for VR2 since part is in series.	No part problem detected.
T2	Transformer	B201627-001	Possible overstress in TWTA 24-17 HV module S/N 002	No part failure mode detected.
J1, J2	TWT RF connector		RF output power dropped during thermal vacuum test of TWTA S/N 14-2 and 14-25	Cause of failure 1. Pin/contact misalignment 2. Large braze fillet on pin 3. Ground spring loose 4. Possible oversized pin/ undersized contact resulting in point pin to contact mating TWTA S/N 14-24 and 14-25 connectors have been reworked.

Failure of helix sense resistor R_1 (1500 ohms) or R_2 (2250 ohms) to open would increase helix trip sensitivity from 6 to 2.67 and 4 mA, respectively. These resistors see high-power transients during TWT defocus transients (approximately 1 watt), while their nominal rating is 0.10 watt. This failure is not seriously considered for the following reasons:

a) The failure mode to open for power transients is very unlikely.

b) With one resistor failed open, the helix trip level is still not reached.

c) The bias converter must have started and is operating normally. The heater inverter is driven from this supply.

d) The high-voltage inverter transistors have not failed short.

The bridge rectifiers have a degree of redundancy built in. They are made up of two series elements in each leg (8 rectifiers/package). Each rectifier has a peak reverse voltage rating higher than the applied voltage stress level. For this reason, failure modes to short should have no effect, and failure modes to open will increase output ripple slightly but not cause shutdown.

In addition to the parts on Table 6-1, a survey was made of all known vendor part failures identified as a result of part-level qualification tests. Although one part (i.e., JANTXIN751A) was common to the Table 6-1 investigation, the discrepancy was not identified, as related to suspect TWTA circuit operation. The results of this review are given in Table 6-2.

One item on Table 6-1 requires mention. Two RF output power anomalies were observed during the 18-day thermal-vacuum temperature cycling test. These were eventually isolated to problems with the input RF connector, as listed in Table 6-1, which were reworked to correct the problem. These anomalies are not related to the orbital failure, but did arise during the course of our investigations. They have been replaced and retested. The details of the parts investigations summarized here are included in the Appendix.

Table 6-2. HAC/EDD TWTA Part Failure Summary. (One part with a failure history is common to Table 6-1, but the discrepancy is not related to anomalous TWTA operation.)

Part Type	Part No.	Type of Failure	Cause	Resolution
Capacitor (wet slug) tantalum	B202114-004 B202114-002 B202114-003 (908557-340) (Sprague)	During qualification test, noted 1.1 microamp leakage after temperature cycle specification is 1.0 microamp maximum	Unknown; all parts passed leakage current after 2000 hour life test	Vibration test on all flight parts. Do not use in 19-volt supply.
Diode	JANTX1N751A (Motorola)	Part mislabeled as JANTXV; also 8 parts rejected in X-ray; 1 extra particle, 7 poor chip mounting	Failed PDFA limit (20 percent)	Use as is after inspection without paint and comp. qual, etc.
Operational amplifier	908911-1 (Harris)	No failure - Parts located at El Segundo - needed for production	Previous lot failed and scrapped	Full lot qual on 11 pieces.
Diode bridge	B200385 (JANTX1N4946) LDC 7543 (Unitrode)	Failed x-ray PDA limit	Apparent voids in potting epoxy due to to improper epoxy mixture	Use as is after successful completion of miniqual test.
Resistor	B850200-080 (Caddock) used in low-level high-voltage module	Large increases of output high voltage after low temperature. Turn on test regulation problem	Resistor cracked due to temperature excursion See ECN A21483	Replace with a larger resistor S/N 009 and up in all high-voltage modules.
Diode bridge	B200385-001 LDC 7609 (Unitrode) JANTX1N4946	After HTRB, two diode bridges had leakage current in excess of 2.0 microamp; read 2.7 and 3.5 microamp	Unknown - lot qual was completed	Use as is; HAC/EDD engineering judgment; no response to justification request.

7. PRODUCT DESIGN EVALUATION

7. PRODUCT DESIGN EVALUATION

This part of the investigation concerned itself primarily with the packaging of the TWT. Particular emphasis was placed on the design of the collector assembly after the S/N 14-15 TWTA failure had been observed. The product design investigation involved a review of the drawings, process specifications, and manufacturing visual aids, as well as actual examination of representative hardware as available.

7.1 UNIT PACKAGING

The drawings, in conjunction with the process specifications and manufacturing visual aids, appear adequate to fabricate and assemble the units. Critical parts placement and wiring are identified and controlled on the drawings adequately. The review did identify several potential design problems and some concerns:

a) The subassemblies are densely packaged, leaving little margin for workmanship errors during assembly, cleaning, and potting.

b) The high-voltage assemblies have detail parts with sharp edges and points, which is not considered good high-voltage design practice.

c) In reworking the high-voltage module, there are occasions when the high-voltage potting material is cut away to replace components, then the area is cleaned, refilled with new potting material, and cured. If this new bond line is not homogeneous, there will be added creepage paths in the high-voltage module which could permit an arc.

d) Thermal analysis and testing indicate areas in the high-voltage module and the TWT collector at acceptance level can be approximately 200°F. These elevated temperatures in a vacuum cause concern that some degradation of dielectric strength of the potting material could occur and permit an arc.

e) The wiring that interconnects the component mounting boards in the semiconductor module are routed near or over sharp metallic edges, such as bifurcated terminals and the ground plane located at the outer perimeter of the printed circuit boards. After the component mounting boards are folded into the module configuration, the assembly is potted with foam. The folding or foaming operation could move the teflon-insulated wires against the sharp metallic edges, causing the teflon to cold flow and a subsequent short. The wiring should be protected from sharp edges to eliminate this potential failure mechanism.

With two exceptions, these concerns are potential problems and have not caused any TWTA failures. The concern involving workmanship does relate to specific failures, however; two TWTAs have failed due to high-voltage arcs in the collector end of the TWT. In order for the encapsulation system to operate properly, it is necessary to perform the cleaning, conformal coating, and potting process very precisely. Any minor discrepancy in this processing can cause the finished TWT to contain voids and delamination in the potting system which can give rise to high-voltage arcs.

The concern involving wiring being pinched or cut by sharp edges is a second one which relates to previous failure. While installed on satellite F7, HLTWTA 14-15 failed in such a fashion as to draw excessive input current and blow the satellite fuses. Troubleshooting the amplifier at the vendor discovered a teflon-coated wire was pinched in the semiconductor module and had shorted to the frame. This semiconductor module was discarded and replaced with a new module.

These workmanship related failures were discovered during ground testing. Although undesirable, they were found and repaired. The TWTA is an assembly of encapsulated modules difficult to inspect or rework in the finished configuration. All 20-watt TWTAs are completed, no additional ones are planned for use on 777 satellites. Therefore, continued reliance will be placed on the unit and satellite test program in lieu of any specific redesign to identi[illegible]solate workmanship related failures.

One specific p[illegible] manufacturing encapsulated assemblies not present in the TWT potting process involves back pressurization. Back pressurization (above 1 atmosphere) during the cure cycle of an encapsulant to reduce the size of potential voids and to assure the flow of encapsulant into the interstices of complex devices is a common and preferred technique. Both the high-voltage module and magnetic processes require it. However, the TWT process does not, even though the encapsulating resin is filled and more viscous than the resins used in other high-voltage areas. Other than this one apparent weakness, the encapsulation process seems well documented and controlled.

7.2 THERMAL EFFECT ON ENCAPSULANT

The thermal stress analysis discussed in Section 9 of this report pointed out the significant stresses induced in the potting material and conformal coating from temperature cycles and thermal gradients. Thus, a specific study was undertaken to understand the thermal properties of the TWT potting material. Initial steps in this study were performed as part of the anomaly investigation and are discussed below. Work is continuing in an attempt to better understand these properties.

The thermal stability of the polymeric encapsulants at the operating temperature of the TWTA has been a continuing question. In an attempt to gain some insight regarding their anticipated service life, the encapsulating materials were subjected to thermal gravimetric analysis (TGA) and differential scanning calorimetry measurements (DSC).

The conformal coating material used in the tube collector was not tested because of a lack of sufficient sample. These tests proved to be somewhat inconclusive in that they indicated that major thermal decomposition of these materials does not occur until temperatures in the neighborhood of 260° to 300°C are reached. Both these materials are urethane elastomers and are subject to thermal reversion (depolymerization) at considerably lower temperatures; however, this reaction mechanism may not be accompanied by a significant weight loss and would be undetected by TGA. Likewise, the energy change accompanying such a reaction may be small and masked by the filler content of the collector potting material. An endothermic reaction was noted in the DSC trace of the high-voltage module encapsulant at 195°F.

The TGA/DSC data were not reduced so that estimates of life time at lower than the indicated decomposition temperatures could be made because such estimates assume that the mechanism and kinetics are the same at the lower temperatures. It would not take into account chemical decomposition (reversion) which occurs without any apparent loss in weight.

Vacuum weight loss measurements of the three polymeric materials were made using a standard measurement technique which subjects the sample to a temperature of 125°C at 10^{-6} torr for a period of 24 hours. Total weight loss (TWL) and volatile condensible material (VCM) collected on a plate in close proximity and at 25°C are determined. These tests were performed at the standard 125°C and at a lower temperature more representative of TWTA

temperatures. The standard, but arbitrary, acceptance criteria for the 125°C test is 1 percent maximum TWL, 0.1 percent at VCM.

Results obtained were as follows:

	TWL (%)	VCM (%)
High Voltage Module Encapsulant (PR 1535)		
24 hours at 125°C	0.83	0.08
64 hours at 82°C	0.59	0.01
Collector Encapsulant (Adiprene L-100 - castor oil)		
24 hours at 124°C	0.17(0.55)	0.04 (0.13)
64 hours at 82°C	0.19(0.61)	0.004(0.13)

NOTE: Numbers in parentheses based on resin content.

	TWL (%)	VCM (%)
Collector Conformal Coat (Epon 101 - Versamid 115)		
24 hours at 125°C	3.54	0.28
24 hours at 100°C		

The collector conformal coat material exhibits an excessive weight loss, probably attributable to entrapped solvent, which the cure cycle failed to drive off. This sample was cured at room temperature, as was the conformal coating on the flight tubes. It was not, however, subjected to the 1/2 to 1 hour of bakeout at 85°C which occurs immediately prior to encapsulation. A more representative sample has been obtained and the test is described in Section 7.3.

The maximum operating temperatures of the polymeric materials have been determined by actual test to be near 100°C. Such temperatures are very near maximum service temperatures for these materials. The encapsulants progressively darken at this temperature and may become more embrittled or chemically revert. There were little direct materials data to demonstrate their satisfactory performance at temperatures over the required service life. Although a thermal stress analysis has not been performed, and indeed would be difficult, it is known that at these relatively high temperatures, the physical properties of these materials change rapidly with incremental temperature changes, and a few degrees may make the difference between satisfactory and marginal performance. There is evidence that thermal stresses are of sufficient magnitude that anything

other than near perfect surface preparation can ultimately produce a bond failure and subsequent electrical failure. It would be much more desirable to have a design which is more forgiving of process variables.

In order to obtain some understanding of the possible deleterious effects of rework on the TWT, an experiment was run to measure the corona inception voltage of the repaired encapsulant and virgin block.

Two leads were potted in a block of PR 1535, with approximately 1 inch of each lead running parallel to the other and separated by about 0.060 inch. Corona inception voltage (CIV) was then measured, with the external leads that protrude from the block immersed in freon. Following the initial measurement, the PR 1535 was dug out, exposing the leads. CIV was again measured. The dug out area was then filled with PR 1535 using the same rework procedure as used in flight modules. A CIV measurement was taken. The results of the CIV measurements are listed below:

Initial CIV Reading:	5,900 volts
Second CIV Reading:	4,500 volts
Final CIV Reading:	6,000 volts

Also it was noted by the TWTA vendor that in the construction and test of over 100 flight high-voltage modules, as well as numerous engineering model modules of the type used in the 1202 HLTWTA, a single situation has been encountered which involved high-voltage arcing or breakdown through a cleavage crack at a repair interface in the PR 1535.

The initial thermal analysis of the HLTWTA, later verified by thermal evaluation testing, indicated the collector temperature would be as hot as 203°F during warm periods of orbit operations. A series of tests was performed by the TWTA vendor to determine whether these operating temperatures were degrading to the potting compound used in the TWTA. These tests involved subjecting multiple samples of the potting compound to various temperatures (75, 100, and 125°C) for up to 5,400 hours (225 days) and periodically measuring their resistivity. These tests showed that insulation resistance is related to temperature and time at temperature:

a) The 75°C samples increased in resistivity from an initial average value of 3.7×10^{11} ohms to a final average value of 8.6×10^{11} ohms.

b) The 100^{o}C samples increased from an initial average value of 2.1×10^{11} ohms to 4.5×10^{11} ohms after 550 hours, then decreased to a final average value of 1×10^{11} ohms. The onset of the decrease in resistivity coincided with the blackening of the samples.

c) The 125^{o}C samples decreased from an initial average value of 3.5×10^{11} ohms after 550 hours and remained between 0.1 and 0.35×10^{11} ohms throughout the duration of the test. The large decrease in resistivity coincided with the blackening of the samples.

d) The resistivity of a sample tested at 125^{o}C in a nitrogen atmosphere was quite similar to the 125^{o}C air samples, except only the PR 420 primer blackened and the PR 1535 turned darker amber.

From the results of the test, it was concluded that the cured polyurethane potting compound, PR 1535, should not be used in applications above 100^{o}C where a minimum MSFC-SPEC-202B insulation resistance of 1 x 10 inch ohms is used as a design requirement.

7.3 EVALUATION OF TWT POTTING SYSTEM

An investigation of in-flight failures of TWTAs and continuing manufacturing yield problems has resulted in a concern that some HEDD TWT package designs are marginally compatible with the properties of the tube potting material and underlying conformal coat/primer system. Stress analysis of suspected critical areas of the tubes, where potting approaches total confinement, has been difficult not only because of complicated geometry, but also because some material properties were ill-defined and small variations in some (i.e., Poisson's ratio) can produce large variations in calculated stress. Adherend contamination problems have been suspected because of difficulty in cleaning and inspecting the recesses of the TWTs which require adhesion. Adhesive properties of the system were unavailable, and simulation of suspected contamination levels to obtain bond strength data representative of bonds attained within the TWTs is virtually impossible in laboratory specimens. Laboratory tests can, however, provide relevant information relating to optimum property values and trends as a function of exposure environments. One purpose of this test

was to verify materials performance at a temperature ($240^{o}F$) which seems high for this class of materials, but which will exist in the collector of the DSCS II 40-watt tube.

A number of tests have been performed to better define the properties of the materials in relation to the analytically derived requirements over the operating and test thermal environment of the tubes.

Failure analyses of tubes have indicated, when the failure site was located, that tube arcing has generally resulted from an adhesion failure rather than a breakdown within the bulk material. For this reason, the TRW test program focused on the determination of bond strength of the TWT potting system. The filled potting material is quite viscous, normally worked hot, and vacuum-degassed and vacuum-poured to prevent bubbles in the potted tube assembly. The process is not amenable to the fabrication of thin bond line adhesion test samples. For the purpose of this test, the material was vacuum degassed while hot, but was subsequently applied to the adherends at ambient pressure. As a result, the bonds were not void free and the measured bond strengths were less than ideal. As a comparison, room temperature flatwise tensile strength for control samples, as reported herein, varies with the adherend but is 159 psi on solvent-cleaned alumina with bond failure, while HEDD reports cohesive failure in the potting material at approximately 350 psi when the sample is vacuum poured against grit blasted alumina.

7.3.1 Test Matrix Comments

Of the adherends present in the high-voltage areas of the tube, only alumina and solder plate were tested. Beryllia is a third material which could have been tested; however, the difficulty in acquiring correctly sized and grit blasted samples led to its deletion in the interest of expediency. Samples were also prepared using etched aluminum as an adherend. Although some tubes present an aluminum surface to be bonded by the potting material, its inclusion here is more as a control or standard.

A primer, PR 420 (Products Research Corporation), was also included, even though it has not been used by HEDD in TWTs. The primer is used by

HEDD with another urethane elastomer in the high-voltage modules of most TWTAs. Its inclusion here was based mainly on a concern that the HEDD conformal coating was being used beyond its practical upper temperature limit.

The planned test included a series of peel strength determinations. Previously mentioned difficulties in preparing samples with this potting material made it impractical to prepare samples of adequate quality, and this determination was deleted from the test.

One of the early concerns for the suitability of the Adiprene system at the upper test temperature was the susceptibility of urethane elastomers to thermally revert. Discussions with DuPont personnel confirmed that they would expect thermal reversion to occur with extended exposures at temperatures approaching 250°F. A series of hardness samples were prepared and aged in air at various elevated temperatures. A marked softening of the material was noted after aging for 2 weeks at 240°F. Continued aging for a total of 3 months caused an apparent rehardening of the samples. When these samples were cut open, it was discovered that the interior portions had continued to soften, while the exterior was apparently undergoing some oxidation process which was producing the crust, causing the apparent hardness increase. A repeat of this test produced the same results in air, but failed to produce either softening or hardening when the samples were aged in vacuum. Since true thermal reversion should be independent of pressure or oxygen environment, the DuPont staff was again queried. They conjectured that there was sufficient moisture in the 240°F air environment to produce a hydrolytic reversion. All adhesion samples aged 1000 hours were aged in air, and although the only moisture access is edgewise into the bond area because of the metal adherends, there is no clear indication whether the bonds were moisture affected. Shrinkage specimens may also have been adversely affected by this phenomenon. It should be remembered that TWTs are normally used in a vacuum environment but are also exposed to long periods of burn-in in air.

7.3.2 Results

7.3.2.1 Shrinkage

Shrinkage measurement of the Adiprene potting system was obtained from 5-inch-long half-cylinder sections prepared by pouring the material into

and curing it in a mold coated to prevent adhesion. The change in length upon completion of the cure cycle was noted and the samples then aged to determine whether further shrinkage would occur.

Measured Cure Shrinkage	= 0.56%	HEDD Value = 0.56%
Total Shrinkage (Cure + Aging)		
After 15 days at 240°F	= 0.80%	
After 42 days at 240°F	= 0.90%	
After 90 days at 240°F	= 2.90%	(reversion indicated)
After 15 days at 150°F	= 0.66%	
After 42 days at 150°F	= 0.70%	

7.3.2.2 Hardness

Shore "A" hardness values as a function of aging are one indication of the stability of the system. Because of surface effects which may occur, they are really only an indication of the presence of some aging phenomena or as a quality measurement for comparison with prior or subsequent lots of the same material. Hardness is measured at room temperature.

Shore A hardness as cured	= 87	HEDD Value = 88	
After aging as indicated:	200°F	220°F	240°F
15 days in air	85	82	76
24 days in air	82	79	73
33 days in air	80	76	72
39 days in air	81	76	74
49 days in air	81	74	74
76 days in air	81	80	85
42 days (no hardness change) in vacuum			87

7.3.2.3 Coefficient of Expansion

Measurements using a quartz tube dilatometer indicate a constant coefficient of linear expansion over the temperature range of concern, with a significant reduction occurring below the glass transition temperature.

Glass transition temperature -63° F HEDD Value -62°F

Coefficient of expansion -300 to -63°F = 21×10^{-6}/°F

Coefficient of expansion -63 to 180°F = 72×10^{-6}/°F

7.3.2.4 Lap Shear Strength

Lap shear samples were prepared using three different adherends (aluminum, alumina, and fused solder plate) and two different primer systems (the HEDD epoxy coating made from Epon 1001 and Versamid 115, and PR420, a commercial primer system for urethanes). The aluminum surfaces were prepared by standard Forest Product Laboratories (chromic acid) etching; all other surfaces were solvent cleaned with isopropyl alcohol only. The HEDD primer/potting systems were prepared and cured in accordance with HEDD procedures, except for the previously mentioned application of prepared material which was done at ambient pressure and temperature. PR420 primer was air dried for a minimum of 1 hour.

Samples were tested at room temperature, 160, 200, and 240°F, both before and after aging for 1000 hours in air at each elevated test temperature. Values obtained are reported in Table 7.3-1.

7.3.2.5 Flatwise Tensile Strength

These samples were prepared and tested in a manner similar to those for lap shear strength, except no samples using PR420 primer were made. Test data are also summarized in Table 7.3-1.

7.3.3 Discussion

Cure shrinkage is a function of cure temperature and can be reduced appreciably, as recently demonstrated by HEDD during their investigation of the feasibility of a 52°C cure instead of the 85°C which is currently used. This lower cure temperature would reduce shrinkage from 0.56 to 0.22 percent. Continued shrinkage reported as a function of aging at 240 and 150°F may not be applicable because of the previously mentioned reversion reaction to which these samples were subject and because the oxidation would occur at a slower rate in a TWT by virtue of material confinement. These data do indicate, however, and the conclusion is supported by the hardness data, that a material change is taking place as a function of time at temperature in air, and that the reaction will proceed at temperatures as low as 200°F and possibly lower.

The glass transition temperature (Tg) reported herein is lower than that previously reported by HEDD but is in very good agreement with a more recent determination. At -63°F, the Tg is below any planned thermal excursions of TWTs, and temperatures below this point should continue to be avoided because of the rapid change in material properties below this point. The value of the coefficient of expansion of this material, measured by a customer, was reported as being approximately 20 percent higher than the 72 x 10^{-6}/°F value reported herein. Other determinations made here, and believed to be of lesser accuracy, ranged as high as 85 x 10^{-6}/°F. Resolution of the TRW/customer differences is currently being worked with a retest at both facilities using specimens from a single casting.

Table 7.3-1. Bond Strength Summary

		Lap Shear Strength [1]					Flatwise Tensile Strength [2]		
	Adherend	Epon 1001/Versamid Primer			PR420 Primer		Epon 1001/Versamid Primer		
Test Condition		Aluminum	Al_2O_3	Solder	Al_2O_3	Solder	Aluminum	Al_2O_3	Solder
Control	72°F	555	133	226	290	252	281	159	555
	160°F	185	130	184	335	283	148	77	306
	200°F	123	94	146	296	243	253	67	165
	240°F	78	58	73	241	225	192	51	156
1000 hrs. 160°F Test	160°F	93(50)	87(66)	140(76)	235(70)	196(69)	158(106)	59(77)	295(96)
1000 hrs. 200°F Test	200°F	43(35)	58(61)	92(63)	121(41)	193(79)	91(36)	27(40)	262(158)
1000 hrs. 240°F Test	240°F	50(64)	29(50)	52(71)	81(33)	57(25)	63(33)	23(45)	108(69)

1. Lap shear strength values, in psi, are an average of at least five samples.
2. Flatwise tensile strength values, in psi, are an average of at least three samples.
3. Numbers in parentheses indicate aged strength as a percent of the corresponding temperature initial value.

7.3.4 Conclusions

As previously mentioned, an inability to vacuum cast the lap shear and flatwise tensile specimens produced voids in the bondlines which materially affected bond strength. Because of this, and other minor specimen fabrication problems, these data do not accurately reflect bond strengths attained in TWTs packaged by HEDD, but do serve as indicators of material performance as a function of adherend, temperature, aging, primer choice, etc. Some other specimen fabrication problems which affected early (unreported) sample strengths were inadequate drying of the alumina filler (which tends to produce a softer cured product) and inadequate mixing (which resulted in some settling of the alumina during cure). All evidence has shown that these problems have been avoided by HEDD with their current procedures; however, they are mentioned here to identify their potential for occurring if their controls are relaxed.

Both the hardness and shrinkage data indicate that some material degradation occurs with extended elevated-temperature aging in air and that the effect is increased with increasing temperature. As previously mentioned, the observed degradation is probably a combination of both hydrolytic reversion and oxidation, neither of which can occur in a good vacuum, but which may be possible during long periods of burn-in if the temperature of the potting material approaches 200^{o}F. Strength-data degradation which was noted after 1000 hours aging at various temperatures as low as 160^{o}F is probably a function of the same degradation mechanisms.

Table 7.3-1 data indicate that adhesive strength is a function of adherend, Al_2O_3 versus solder, when the Epon 1001/Versamid 115 primer is used, with solder being the superior adherend, but that the effect is much less pronounced (and reversed if it exists at all) when PR420 primer is used. A much more noticeable effect is that PR420 priming yielded consistently higher lap shear strengths, approximately twice those attained with the other primer.

Elevated-temperature testing indicates a near linear degradation of bond strength with temperatures from 160 to 240^{o}F, both before and after aging. Some apparent inconsistencies within the flatwise tensile data summary of Table 7.3-1 are most probably attributable to sample preparation difficulties, the lower numbers in these cases being suspect.

7.3.5 HEDD Data

For the past few months, HEDD has also been testing the Adiprene system, mainly to define bulk properties of the material. These data have been presented at various meetings and reviews, and more data are currently being acquired. In the interest of compiling a more complete data summary, a data page from a recent TWT design review package is presented in Table 7.3-2. One comment concerning the Poisson's ratio value reported is that this difficult measurement is highly dependent upon interpretation of the autographic strain curves. If one chooses to ignore strains occurring at very low loads, then Poisson's ratio can be interpreted to be near 0.43.

Table 7.3-2. Polyurethane Potting Compound*
(Adiprene L-100/Caster Oil per/MPS 6-11, Type U, Class 3)
Physical Properties

	Standard 85° Cure	Proposed 52° Cure
Hardness - Shore A	88	88
Density g/cc	2.11	2.11
Thermal conductivity (BTU in/hr-ft^2-$^\circ$F)	9.33	9.50
% Acetone Extractables	0.29	0.23
Infrared Spectrum (IR Analysis)	PGE[1]	PGE[1]
Differential Thermal Analysis (DTA)	ND[2]	ND[2]
Differential Scanning Calorimetry (DSC)	ND[2]	ND[2]
Thermal Gravimetric Analysis (TGA)	ND[2]	ND[2]
Tensile at Room Temperature (PSI)		
Breaking Load	417	432
Maximum Load	464	473
% Elongation at Breaking Load	130	122
% Elongation at Maximum Load	51	58
Tensile[3] (PSI)		
@ + 145°F	357	426
@ 79°F (Room T$^\circ$)	404	461
@ 10°F	1550	1617
% Elongation[3]		
@ + 145°F	20	20 - at break
@ 70°F (Room T$^\circ$)	61	77 - at break
Cure Shrinkage	0.55%	0.22%
@ 10°F	450	451 - at break
Poisson's Ratio		
@ 145°F	0.47-0.50	0.48-0.50
@ 70°F (Room Temperature)	0.48-0.50	0.50
@ 10°F	0.42-0.50	0.43-0.48
Elastic Modulus (PSI)		
@ 145°F	3878	3967
@ 70°F (Room Temperature)	4544	4067
@ 10°F	4533	4700
Glass Transition (TG)	-52°C	-52°C

*Taken from HEDD Design Review Package W-06997.

NOTES:

(1) PGE = Polyethylene Glycol Ester. Standard IR curve for this material.

(2) ND = No difference in values or curves.

(3) Typical values for material at EDD, determined from various batches of material.

(4) Poisson's ratio stated in range of test.
Low/high results.

8. TEMPERATURE CYCLING THERMAL VACUUM TEST PROGRAM

8. TEMPERATURE CYCLING THERMAL VACUUM TEST PROGRAM

Due to the relatively short orbital life of NCHLTWT-1 on Satellite 9438, a review was made of the total prelaunch test program applied to the TWTAs. This test program can be summarized as follows:

a) 2168 hours of power-on burn-in on each HLTWT at $125^{\circ} \pm 15^{\circ}F$ and ambient pressure

b) 168 hours of power-on burn-in on each TWT power supply at $125^{\circ} \pm 15^{\circ}F$ and $<1 \times 10^{-5}$ torr pressure

c) Eight temperature cycles at ambient pressure on each TWT power supply from 60° to $146^{\circ}F$

d) Integration of the TWT and a power supply

e) 332 hours of power-on burn-in for each HLTWTA at $125^{\circ} \pm 15^{\circ}F$ and atmospheric pressure

f) Acceptance test of each TWTA, which includes three-axis vibration (1 minute random per axis) and one temperature cycle thermal vacuum test of approximately 16 hours. Functional tests are run at 60, 100, and $146^{\circ}F$ during this thermal vacuum test

g) Minimum of 150 hours operation on the satellite at room ambient temperature and pressure

h) Approximately 72 hours of operation in hard vacuum during satellite thermal vacuum testing. Temperature conditions during this testing are those established by the satellite thermal control system and represent nominal orbit conditions for eclipse equinox and winter solstice.

With this test plan, each HLTWTA is subjected to less than 100 hours of operation in vacuum conditions.

8.1 EXTENDED T/V TEST PLAN

After discussions with representatives of other programs using similar HLTWTAs, it was concluded that additional confidence could be developed in the remaining HLTWTAs if they were subjected to, and passed, an extended temperature-cycling thermal vacuum test. Also, it was felt that this was a good way to try to induce a failure in a TWTA or TWTAs with a signature similar to the orbit failures. Initial duration was established at 28 days. However, the test was eventually shortened to 18 days to allow time

for accomplishing a minor design change in the power supply which would allow prelaunch disabling of the helix overcurrent trip circuit.

The test plan developed for this extended screening test is included in Appendix D. The test provided for four temperature cycles per day from 60 to 146°F. Also, once a day the TWTA would be commanded OFF and back on again. Continuous recordings were made of each amplifier's telemetry measurement and RF output power. All data were reviewed and attempts made to explain or understand any variations in the recorded data, whether within specification or not.

8.2 SUMMARY OF RESULTS

A total of 18 HLTWTAs made up the remaining lot of flight candidate amplifiers. They were all tested; most passed, some failed. Table 8.2-1 lists each TWTA, with the results of its 18-day test. The failures can be summarized as follows:

a) One high-voltage arcing failure across the end surface of the beryllium insulation under the collector

b) Two mismatched RF input connectors

c) One failure of unknown origin characterized by causing the TWTA to turn itself off due to helix overcurrent within 4 to 6 hours of initiating a thermal vacuum test

d) Two anomalies wherein small helix current transients, not sufficient to cause shutdown of the amplifier, were observed in the first 2 to 5 days of testing. They subsequently cleared up and did not reappear during the remainder of the thermal vacuum.

In retrospect, the extended temperature-cycling thermal-vacuum test was extremely valuable. It discovered six amplifiers which exhibited anomalous behavior and require further evaluation and rework before flight. The tests also identified 12 units which perform properly and can be considered flight candidates immediately. A series of failure investigations was performed on each of the six amplifiers mentioned above.

Table 8.2-1. Extended Temperature Cycling Vacuum Test Exposed Potential Failures Involving High Voltage Arcs and Mismatched RF Connectors

S/N	Extended Vacuum Test Results	Comments
14-15	Failed	Collector arc
14-19	Passed	
14-20	Passed	
14-21	Failed	Helix current transients
14-22	Passed	
14-23	Passed	
14-24	Failed	RF connector mismatch causes small signal gain variations
14-25	Failed	RF connector mismatch causes small signal gain variations
24-19	Failed	Helix current transients
24-20	Passed	
24-21	Passed	
24-22	Passed	
24-23	Passed	
24-24	Passed	
24-25	Passed	
24-26	Failed	Shutoff due to excessive helix current
24-27	Passed	

8.3 TWTA TURN-ON DATA

Because of the transients observed during initial turn-on of F8 HLTWTA-1 and its subsequent failure within 6 days, the turn-on characteristics for all TWTAs subjected to the thermal-vacuum screening test were recorded and reviewed. Selected samples of these data for five of the tubes tested are shown in Figures 8.3-1 through 8.3-5. A review of these

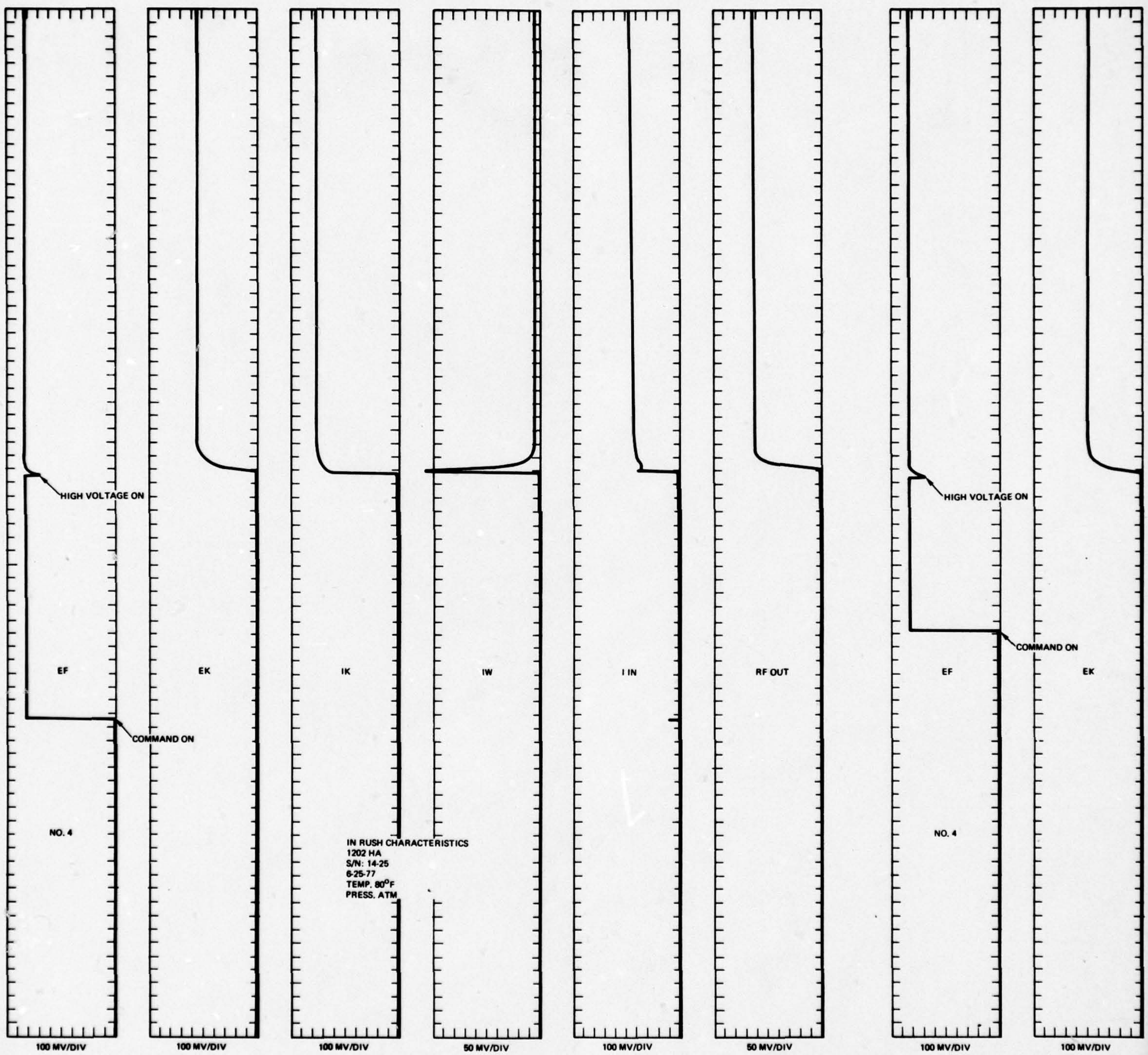
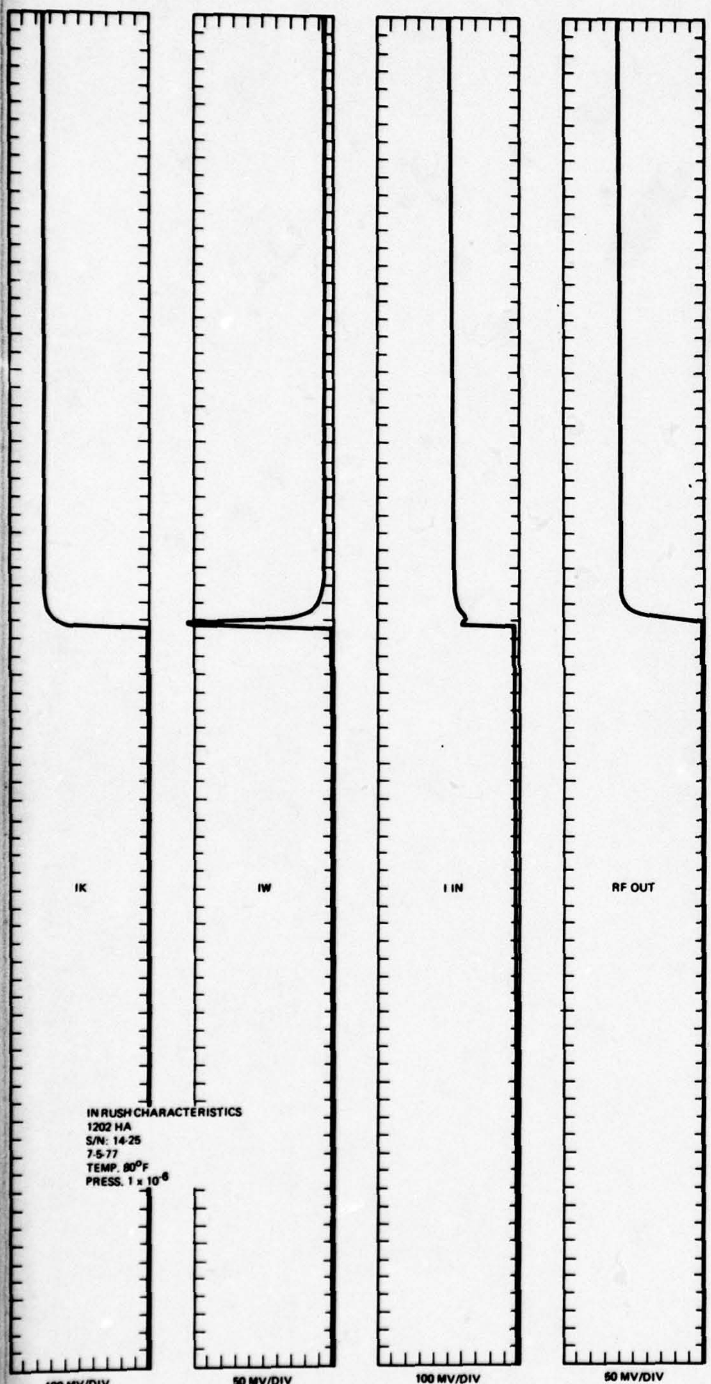


Figure 8.3-1. Turn on Characteristics for HLTWTA S/N 14-25 in Vacuum and Ambient Pressure


IK
IW
I IN
RF OUT
IN RUSH CHARACTERISTICS
1202 HA
S/N: 14-25
7-5-77
TEMP. 80°F
PRESS. 1 x 10-6
100 MV/DIV
50 MV/DIV
100 MV/DIV
50 MV/DIV

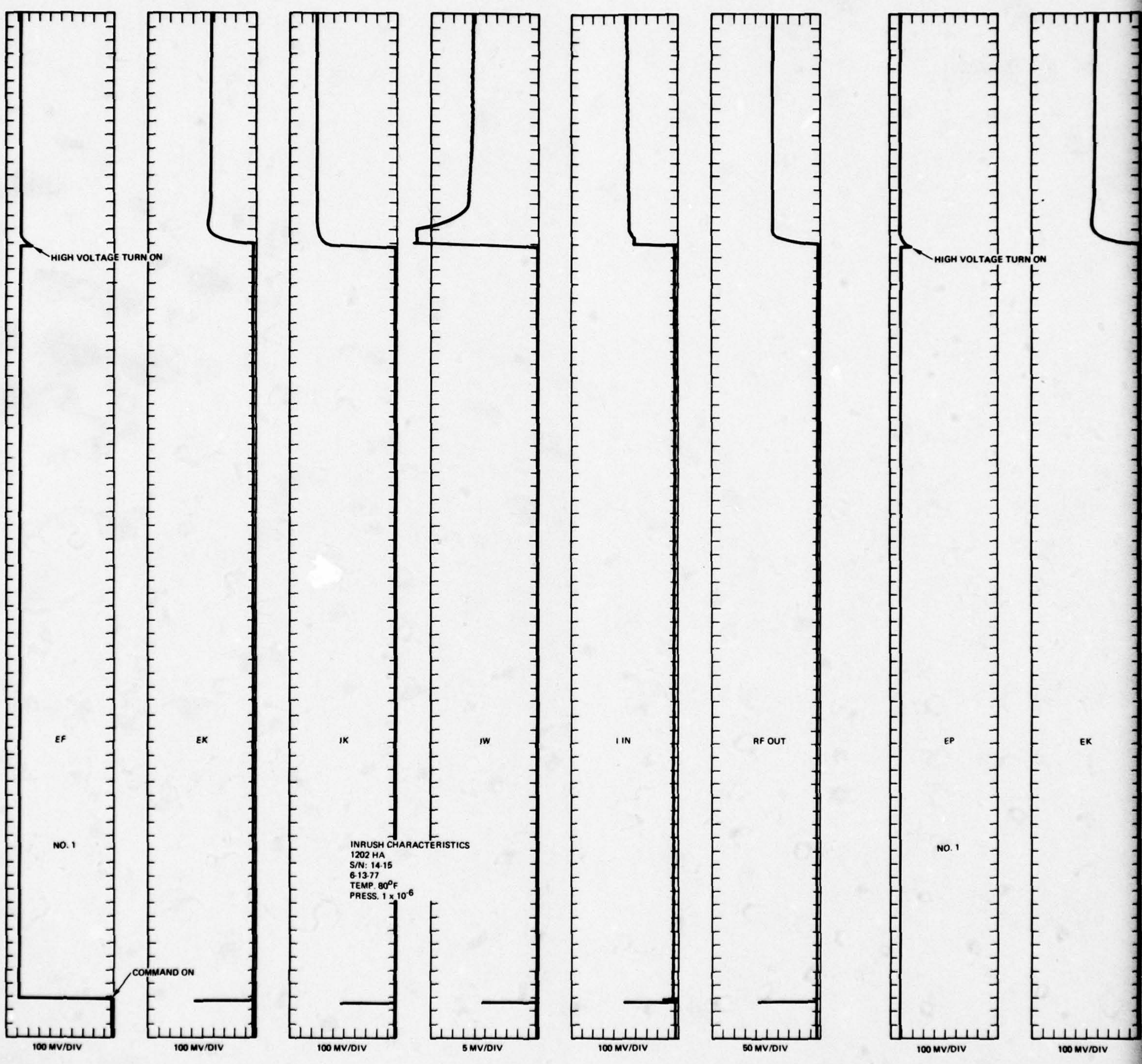
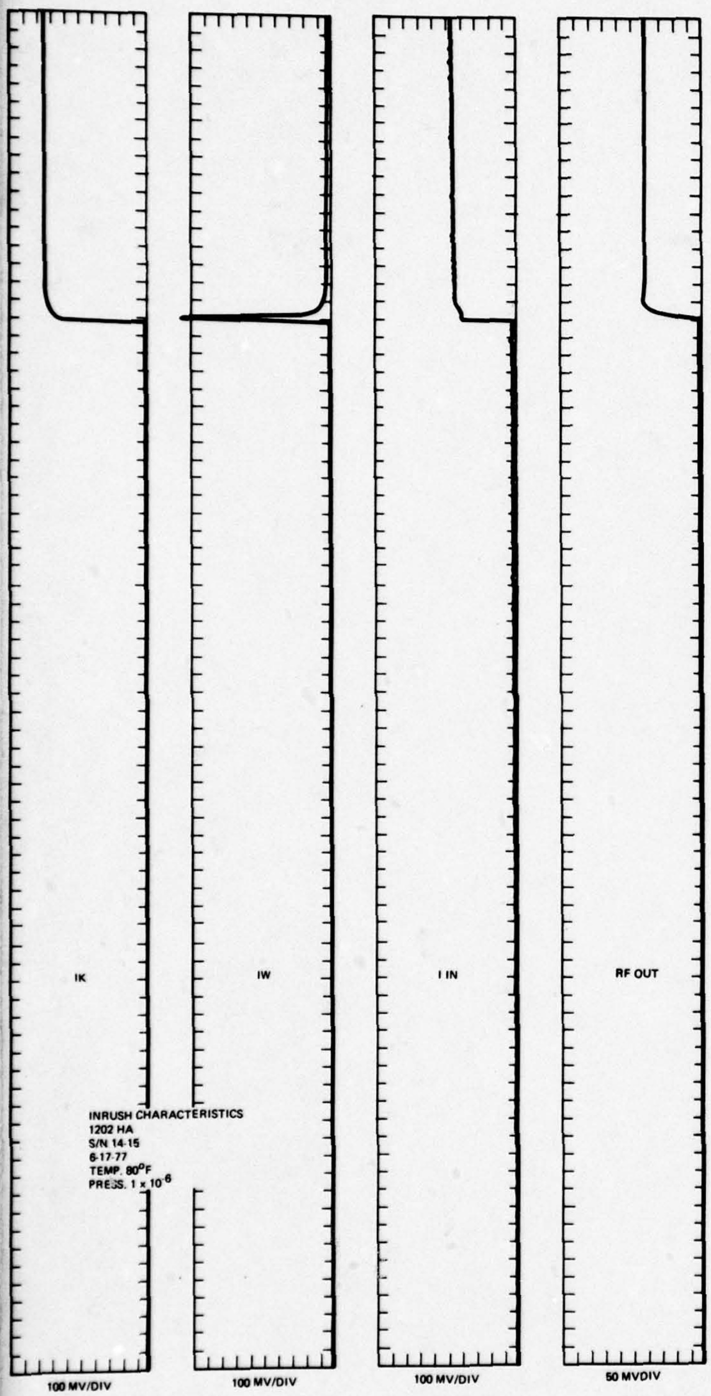


Figure 8-3.2. Turn on Characteristics for HLTWTA S/N 14-15 in Vacuum on 6/13 and 6/17/77


IK
IW
I IN
RF OUT
INRUSH CHARACTERISTICS
1202 HA
S/N 14-15
6-17-77
TEMP. 80°F
PRESS. 1 x 10⁻⁶
100 MV/DIV
100 MV/DIV
100 MV/DIV
50 MVDIV

2

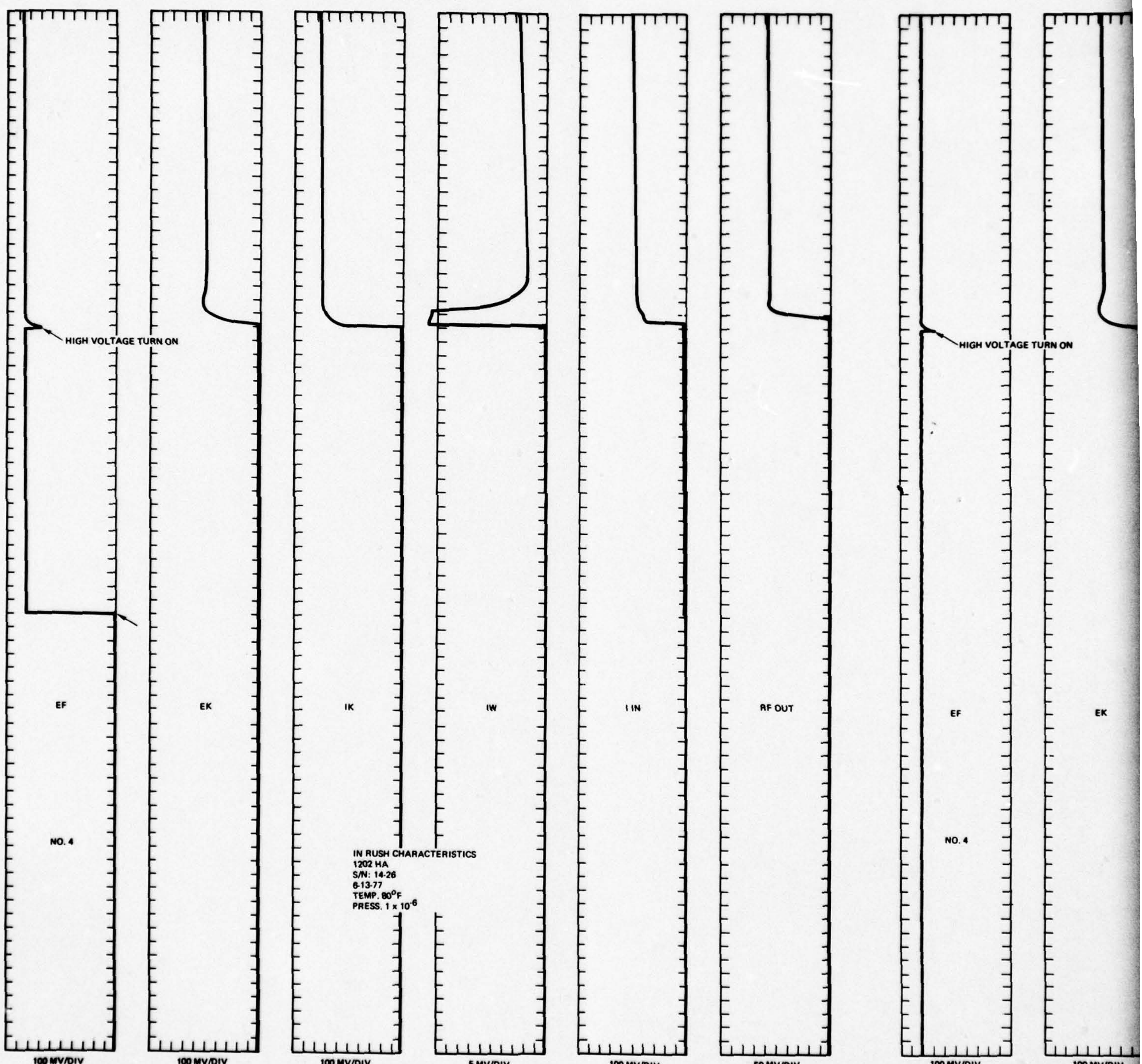
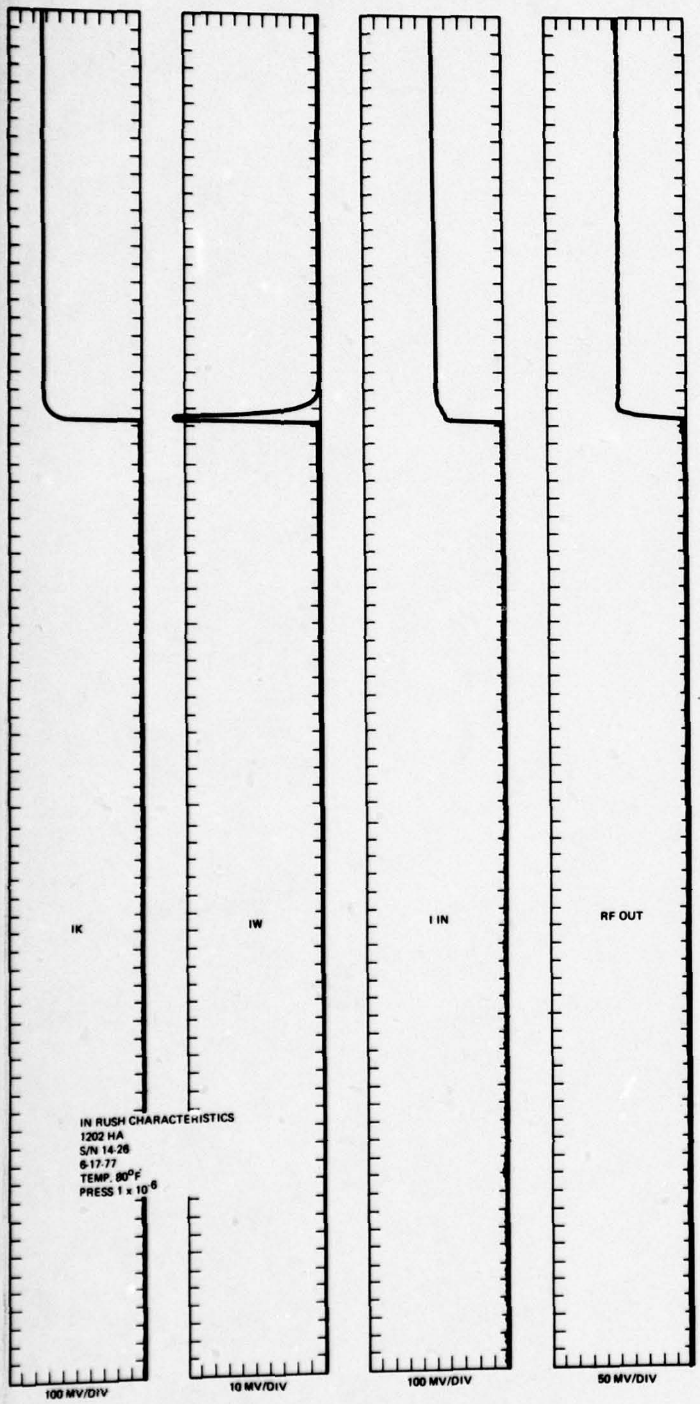


Figure 8.3-3. Turn on Characteristics for HLTWTA S/N 14-76 in Vacuum on 6/13 and 6/17/77


IK
IW
I IN
RF OUT
IN RUSH CHARACTERISTICS
1202 HA
S/N 14-26
6-17-77
TEMP. 80°F
PRESS 1 x 10-6
100 MV/DIV
10 MV/DIV
100 MV/DIV
50 MV/DIV

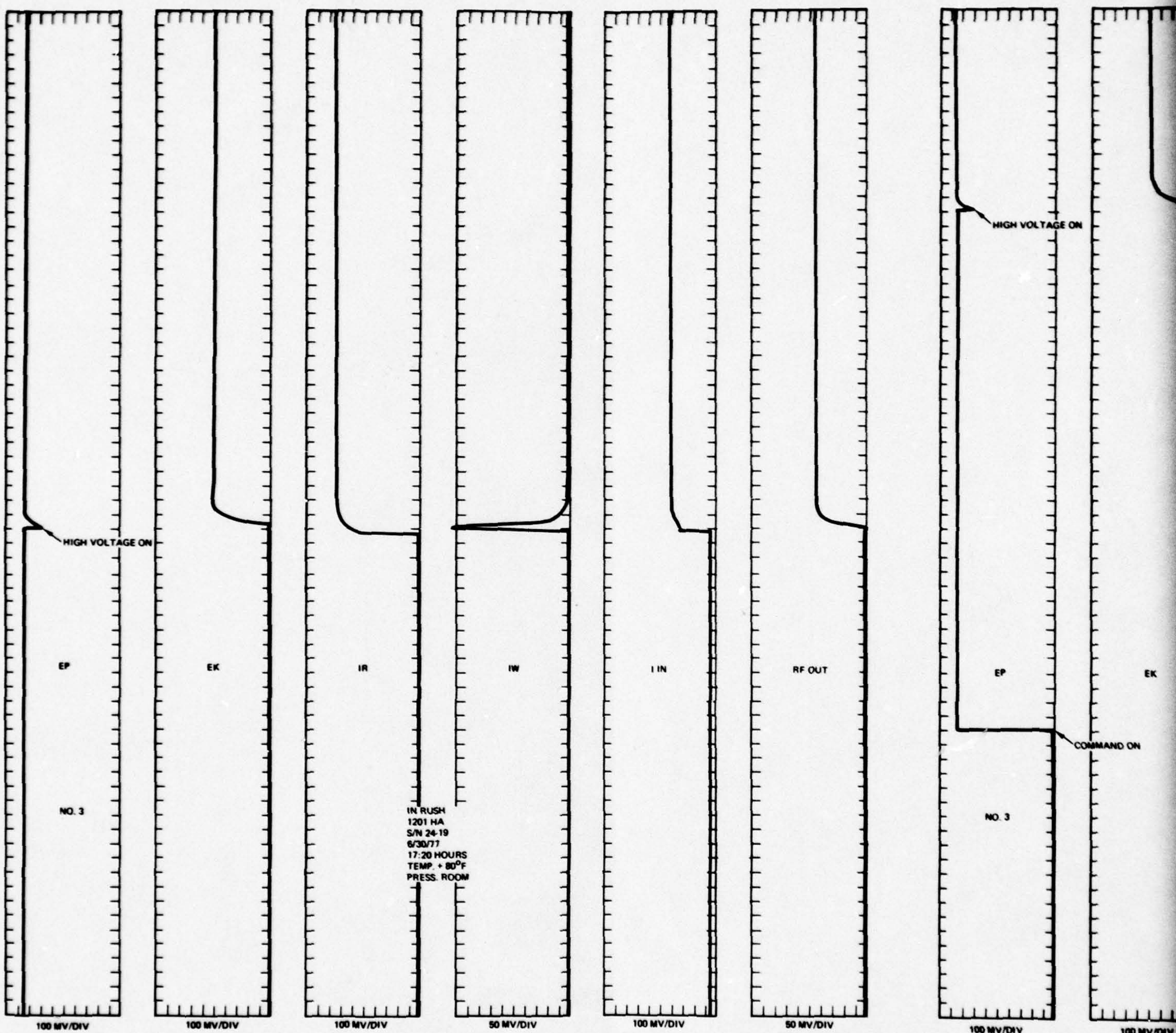
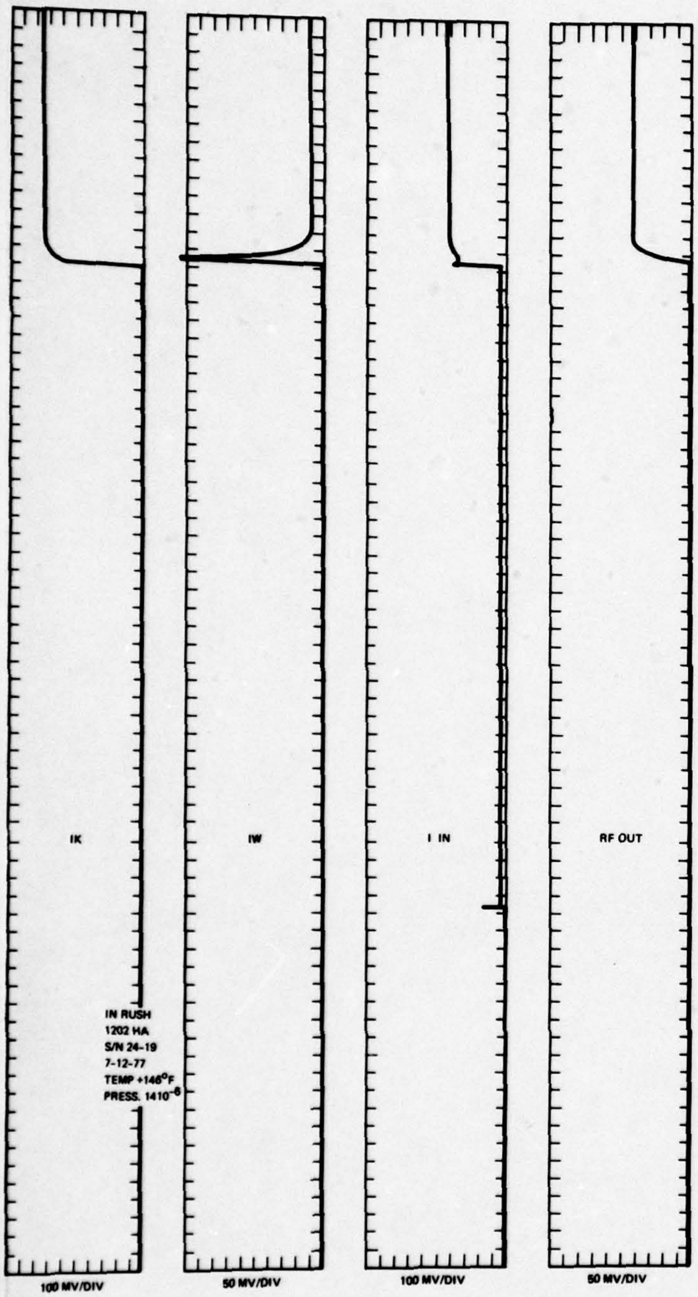


Figure 8.3-4. Turn on Characteristics for HLTWTA S/N 24-19 at Vacuum and Ambient Pressure Conditions


IK
IW
I IN
RF OUT
IN RUSH
1202 HA
S/N 24-19
7-12-77
TEMP +146°F
PRESS. 1410-6
100 MV/DIV
50 MV/DIV
100 MV/DIV
50 MV/DIV

2

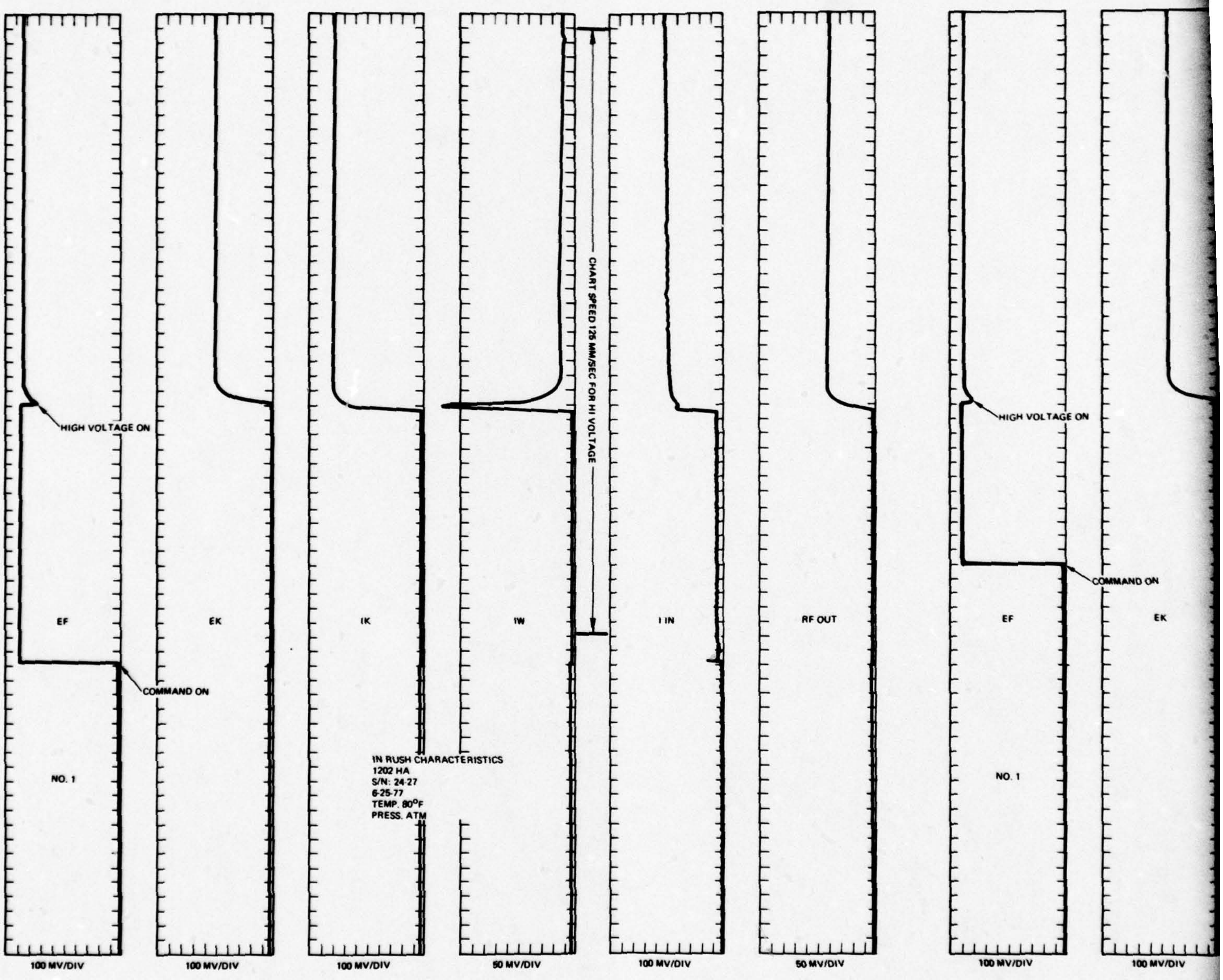


Figure 8.3-5. Turn on Characteristics for HLTWTA S/N 24-27 at Vacuum Ambient Pressure Conditions

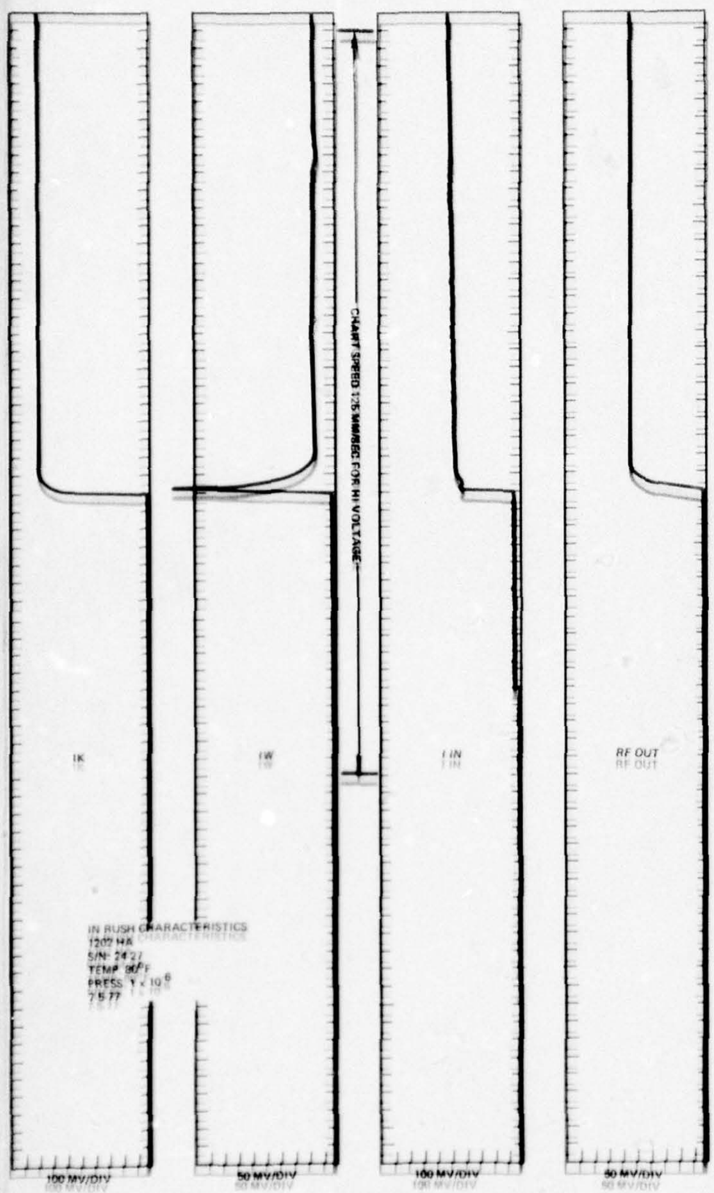


CHART SPEED 125 MM/SEC FOR HI VOLTAGE
IK
IW
I IN
RF OUT
IN RUSH CHARACTERISTICS
1202 HA
S/N: 2427
TEMP 90°F
PRESS 1 x 10^6
7 5 77
100 MV/DIV
50 MV/DIV
100 MV/DIV
50 MV/DIV

curves does not show any significant difference between amplifiers. Of particular interest is a comparison between S/N 14-15, the TWTA which subsequently failed, and the others which did not. Again, the variation between amplifiers which survived the thermal vacuum test is greater than the variation between 14-15 and the rest. The unusual turn-on characteristic of the F8 HLTWTA-1 stands out as different. However, any attempt to explain it can be expressed in only the most speculative terms, and the short-term failure of 14-15 and 24-26, which showed nominal turn-on characteristics, precludes using these data to screen out amplifiers of short life.

8.4 TWT THERMAL VACUUM TEST

In addition to the TWTA thermal vacuum test, a nonoperating vacuum test was performed on two TWTs.

Two 265HB TWTs were placed in a thermal vacuum chamber and high-potential tested (both gun and collector) at 2,000 volts for approximately 3 weeks while being temperature cycled from 40 to 140^{O}F (90 $\pm$50^{O}F) and maintained at hard vacuum. The purpose of this test was to determine the presence or absence of potting/conformal coating voids in high-voltage stress areas. The results were negative in that no failure or problem areas were detected. This test was terminated 11 July 1977 to allow one of these TWTs to be used for satellite thermal evaluation tests.

9. SATELLITE MOUNTING AND THERMAL EVALUATION

9. SATELLITE MOUNTING AND THERMAL EVALUATION

After reviewing the detailed satellite mounting provisions for the HLTWTAs, concern was raised as to possible deleterious effects from the mounting surface on the despun platform not being flat. In fact, it was purposely made not-flat by the addition of three indium gaskets on the cooling plug, which when stacked gave a stepped pyramid configuration 0.015-inch high in the center and 0.005-inch high at the ends. A review of the original development program determined that the pyramid indium configuration was selected to ensure good physical contact from the TWTA baseplate to the platform plug. This improved contact was observed visually from comparing different test configurations. Review of the platform/TWTA thermal analysis showed that lower conductance values for this interface could possibly be tolerated. With this in mind, and spurred by concern over the nonflat nature of this interface and possible mechanical stress it could induce in the TWT, a reevaluation of this interface was conducted. This reevaluation followed two paths of inquiry. Test and analysis were performed to evaluate the mechanical stresses induced in the TWT by the indium pyramid, and a thermal test was performed to determine whether a flatter configuration would operate satisfactorily.

9.1 STRESS ANALYSIS AND TEST

A test was constructed in which a TWT installed in a TWTA chassis and instrumented with strain gages was mounted on a satellite platform and torqued down in a flight configuration. The location of the strain gages is shown in Figure 9.1-1. The TWT baseplate sustained a deformation of 540 and 475 in/in. along the collector mounting "shovel" edges, parallel to the tube's longitudinal axis. Detailed strain-gage data and synopsis of the test are included in Appendix E.

A stress/strain analysis was performed of the collector end of the TWTA as mounted to the satellite in the flight configuration. This analysis modeled the loads due to the mechanical fasteners and the worst-case thermal environment, both individually and in combination. No cold-flow compression of the indium gaskets was assumed. Each material layer, from the aluminum platform plug to the TWT collector, was specifically modeled. These include the indium spacers, potting compound, conformal coating,

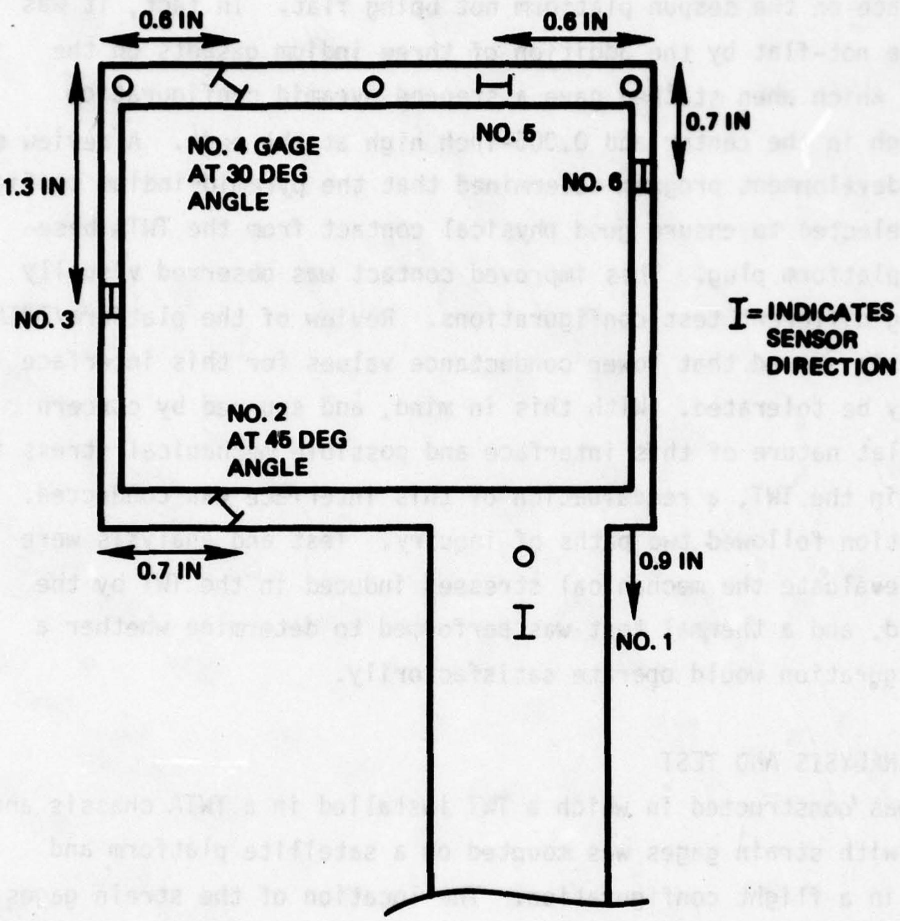


Figure 9.1-1. Strain Gage Locations were Selected to Obtain Data From Which the Mechanical Stress in the TWTA Collector Assembly Could be Calculated

solder, beryllium, copper, and aluminum. A schematic representation of the computer model is shown in Figure 9.1-2. This analysis concluded that the stepped indium gasket configuration did not induce structural failure of the TWTA. It did contribute to the already existing internal thermal stress and strains within the TWT collector end assembly. The analysis showed the solder and copper layers on both surfaces of the beryllium insulation would yield a small amount. Also, the potting compound and conformal coating yielded a small amount under the combined thermal and mechanical stresses. A quantitative summary of the analysis results are given in Table 9.1-1. The area at which the maximum strain exists in the conformal coating and potting compound is shown in Figure 9.1-2. It should be noted that after this investigation, the mounting configuration has been changed to a single 0.005-inch indium gasket for F9 and subsequent satellites.

Table 9.1-1. Mechanical and Thermal Stresses in Collector End of 20-Watt TWTA

	Mechanical	Thermal	Combined	Yield/ Allowable	Units
Aluminum 6061 TC	19,300*	10,283	29,580	35,000	Stress (psi)
Copper (of HC)	22,000	14,300	36,300	30,000/6%	Strain (0.25%)
Beryllium	12,000	16,000	27,500	40,000	Stress (psi)
Solder 63 Sn/37 Pb	0.6%	1.0%	1.6%	>25%	Strain
Conformal Coating	2.2%	2.2%	4.4%	>10%	Strain
Potting compound	11%	6%	17%		Strain

*Compares to a measured value of 21,150 psi in the TWT mechanical stress test.

9.2 THERMAL EVALUATION

To evaluate the thermal effectiveness of the three-layer indium gasket interface, as well as alternative flatter interface configurations, an operating TWTA, instrumented with thermocouples, was installed on a qualification model despun platform and tested in a thermal vacuum chamber. The

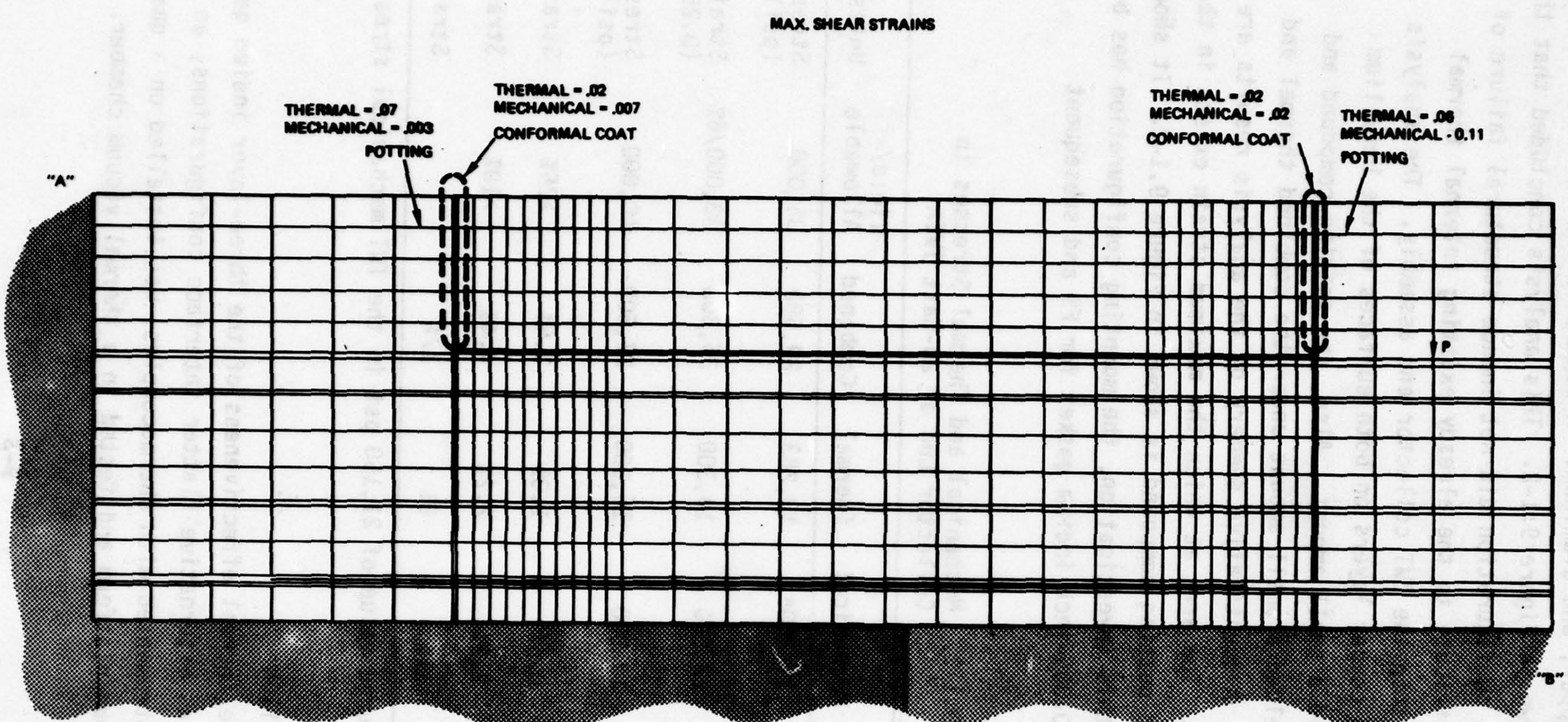


Figure 9.1-2. The Stress Analysis Model of the Collector Assembly of the TWT Assumes the Mechanical Force due to Mounting on the Satellite is Applied at Point P. The Model Further Assumes a Rigid Mounting Surface at Rage A & B

Log 034

test was first performed using the existing three-layer gasket to establish a baseline which could be related to orbit telemetry data. The instrumentation included thermocouples in the same locations on the despun platform as the ones in flight. The different interface configuration tests are as follows:

a) RTV8111 between "TWTA base area" and platform; a 1 inch x 1-1/2 inch 3-mil gold-plated screen at M2, M3, and M4; one 122056-1 5-mil indium gasket over the "aluminum plug;" 6-32 x 1-7/16 screws through the aluminum plug and into the TWT base at P1, P2, P3, and P4; 6-32 fasteners into top of platform at M1, M2, M3, and M4.

b) Identical to Configuration No. 1 except the 6-32 screw through the aluminum plug at location P2 was not installed.

c) Identical to Configuration No. 1 except the 122056-2 and -3 indium gaskets were installed. This configuration was per Drawing 310511 H3.

d) RTV8111 between "TWTA base area" and platform; RTV8111 between "aluminum plug" and tube base; 1 inch x 1-1/2 inch 3-mil gold-plated screen at M1, M2, M3, and M4; 6-32 x 1-7/16 screws through the aluminum plug and into the TWT base at P1, P3, and P4; 6-32 fasteners into top of platform at M1, M2, M3, and M4.

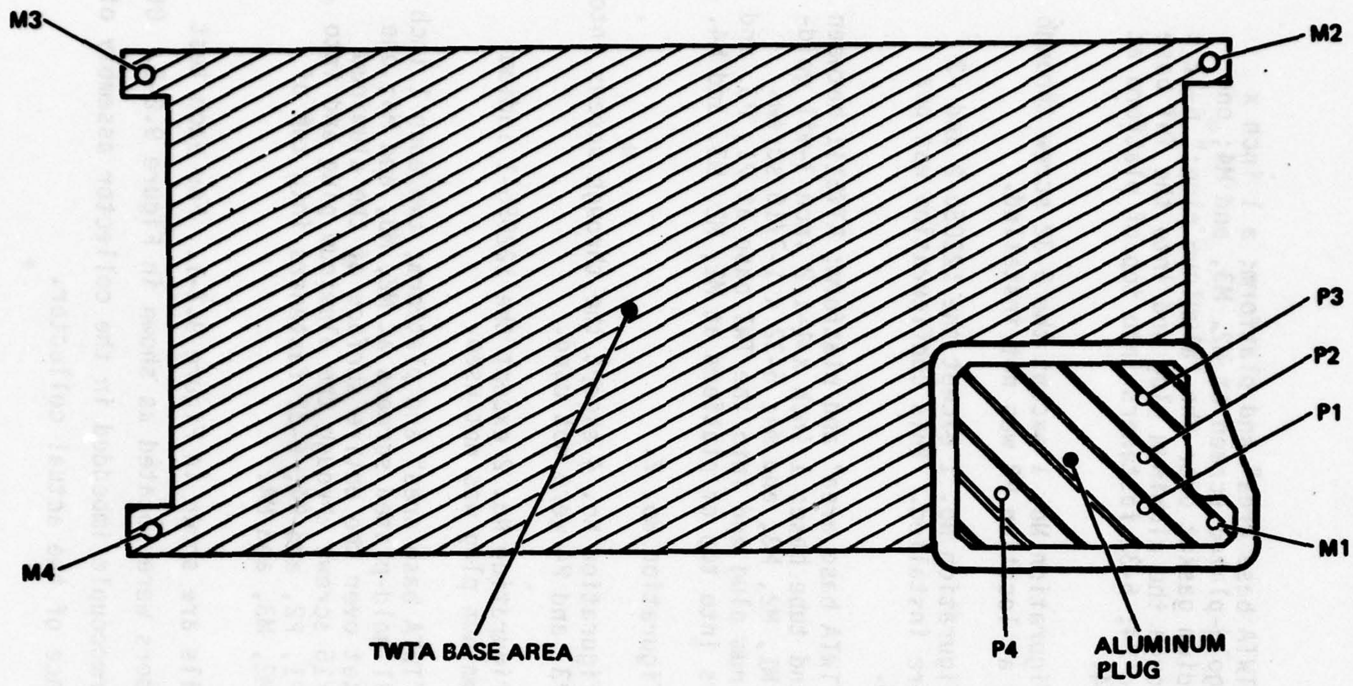
e) Identical to Configuration No. 2.

f) Identical to Configuration No. 4 except the through screws into the tube at P1, P3, and P4 were not used.

g) Identical to Configuration No. 2 except the 122056-1 indium gasket at the aluminum plug was not used.

h) RTV8111 between "TWTA base area" and platform; two each 1 inch x 1-1/2 inch 3-mil gold-plated screens at M2, M3, and M4; one 5-mil indium gasket over the entire surface of the aluminum plug; 6-32 x 1-7/16 screws through the aluminum plug and into the TWT base at P1, P2, and P4; 6-32 fasteners into top of platform at M1, M2, M3, and M4.

The screw mounting details are shown in Figure 9.2-1. For each test thermocouple temperature sensors were located as shown in Figure 9.2-2. Of primary interest was the thermocouple imbedded in the collector assembly of the TWT on the exterior surface of the actual collector.



M1, M2, M3, M4 = HLTWTA MOUNTING LUGS (SCREWS INTO TOP OF PLATFORM)

P1, P2, P3, P4 = HLT TIEDOWN LOCATIONS (SCREWS THROUGH ALUMINUM PLUG INTO TUBE BASE)

Figure 9.2-1. The Mounting Screws Used in the Thermal Evaluation Test Are Identical to the Flight Configuration

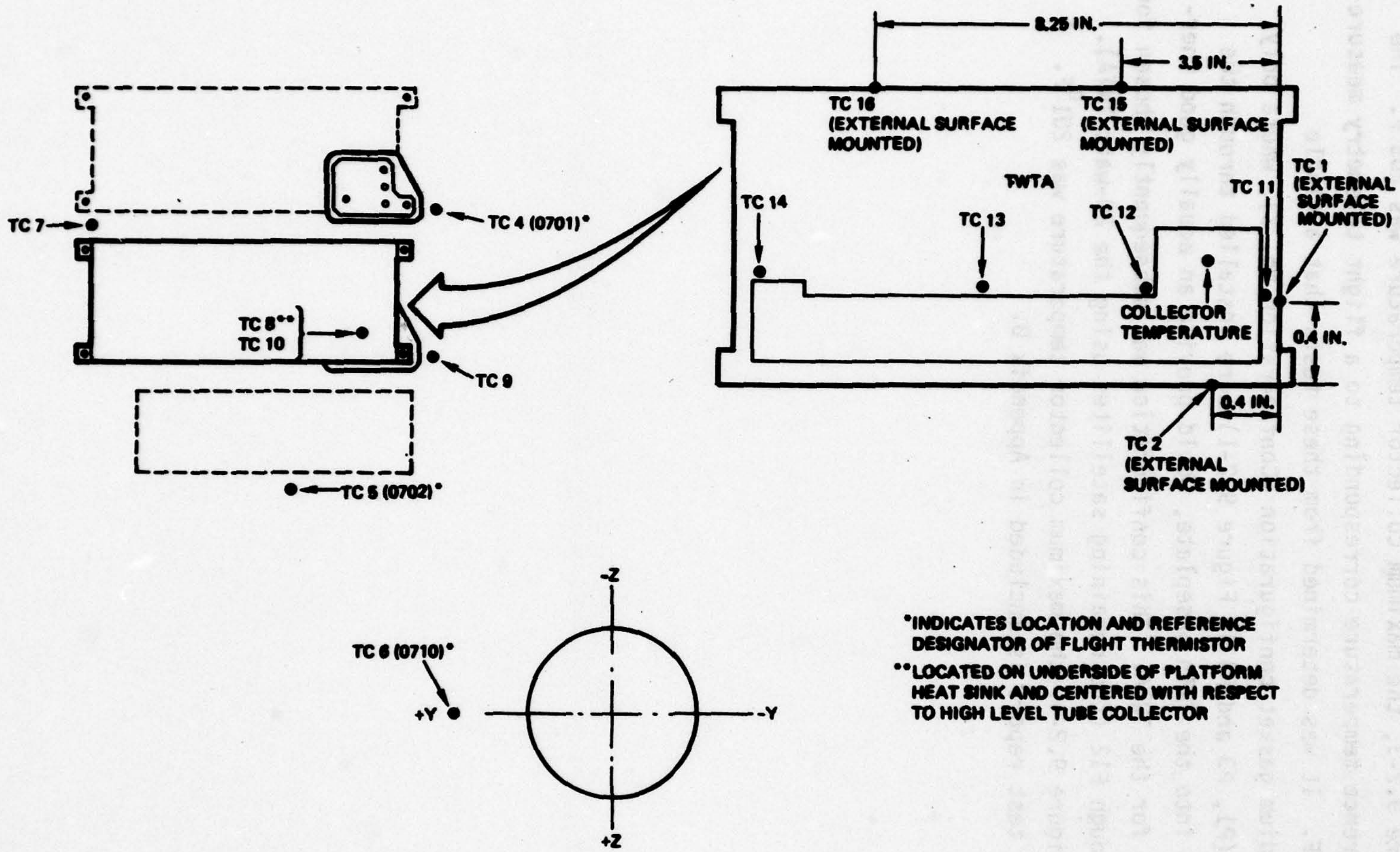


Figure 9.2-2. Thermocouple Locations Were Selected to Provide Specific Collector Data as Well as Overall TWTA and Platform Temperature Data Which Could be Directly Related to Flight Thermister Data

Test configuration three was the then existing flight configuration. As shown in Figure 9.2-3, the maximum collector temperature was 203^{o}F. The platform reference temperature corresponding to a flight telemetry measurement was 113^{o}F. It was determined from these tests that a single 0.005-inch indium gasket configuration (Configuration No. 2), where only three screws (P1, P3 and P4 in Figure 9.2-1) were installed through the platform plug into the TWTA baseplate, would provide an equally good thermal interface for the TWTA. This configuration was subsequently chosen for use on F9 through F12 (the remaining satellites using the 20-watt TWTA). As shown in Figure 9.2-4, the maximum collector temperature was 201^{o}F. A more detailed test report is included in Appendix D.

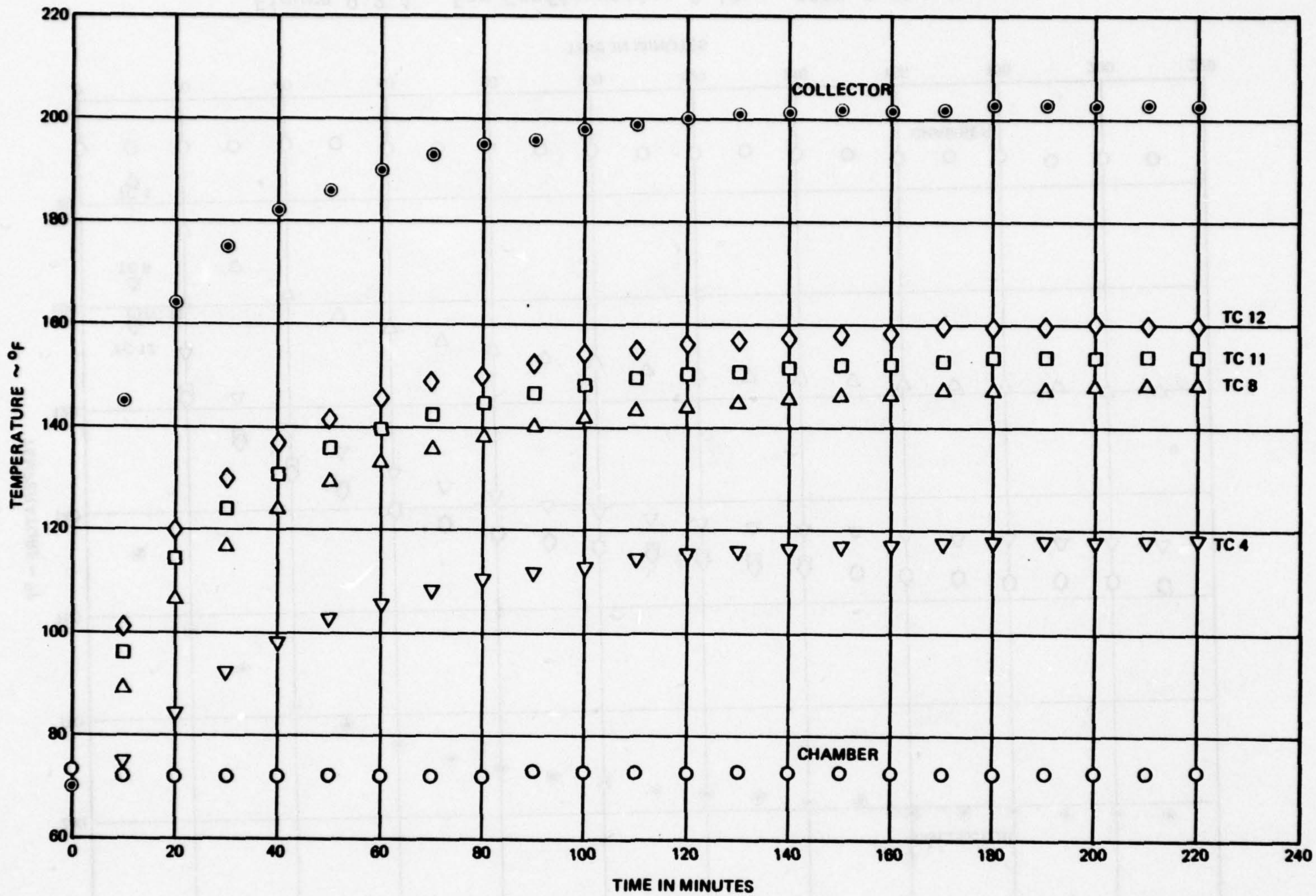


Figure 9.2-3. For the Reference Configuration (No. 3) the Maximum TWTA Collector Temperature was 230°F at a Chamber Temperature of 74°F

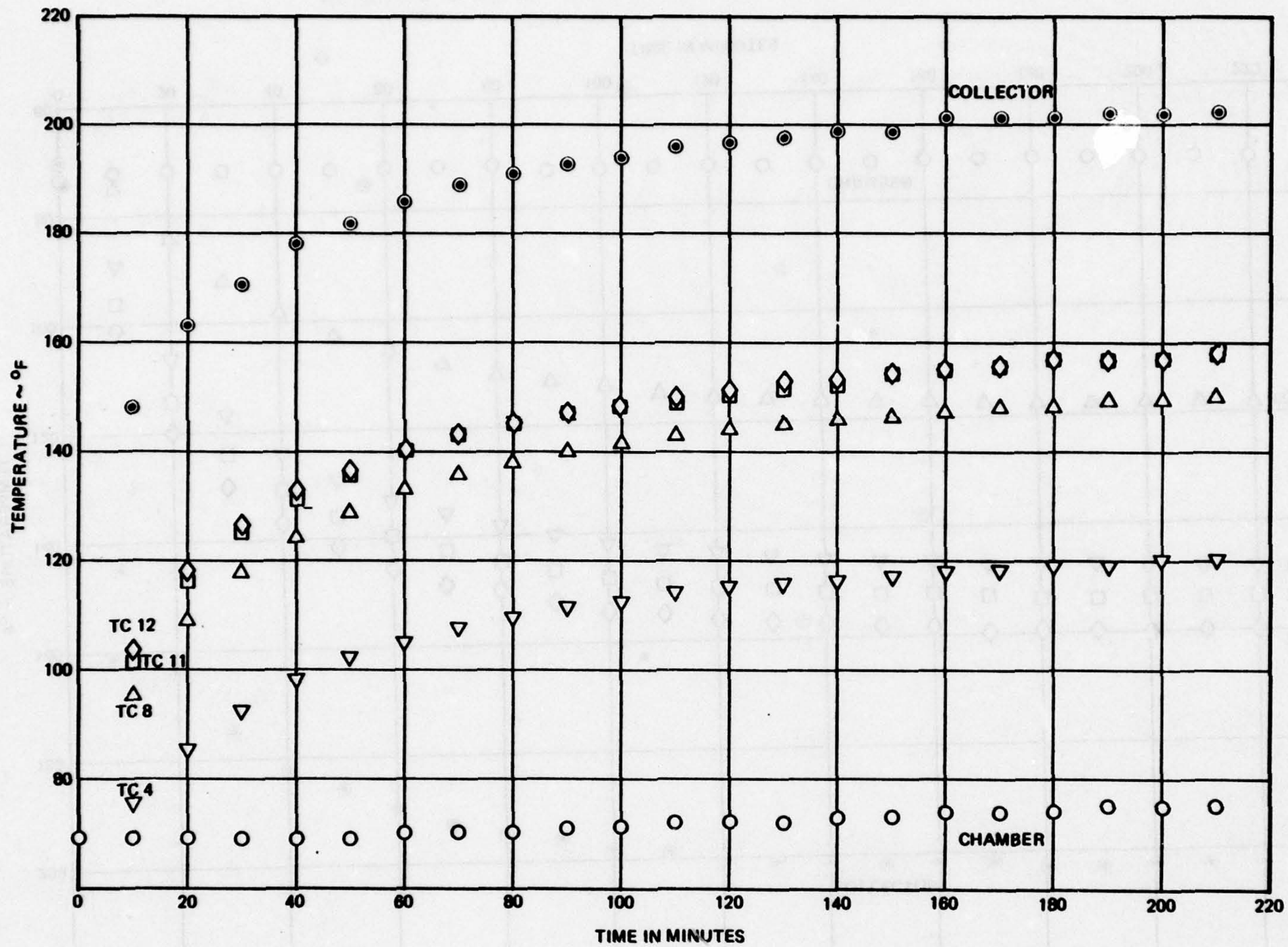


Figure 9.2-4. For Configuration 2 (One .005" Indium Gasket). The Maximum TWTA Collector Temperature was 201°F at a Chamber Temperature of 74°F.

10. FAILURE ANALYSIS ON ANOMALIES DISCOVERED IN EXTENDED THERMAL VACUUM TESTS

10. FAILURE ANALYSIS ON ANOMALIES DISCOVERED IN EXTENDED THERMAL-VACUUM TESTS

Section 8 of this report summarized the results of the extended temperature cycling vacuum tests performed on the 18 remaining HLTWTAs built for F9 through F12. There were six anomalies during this testing. Two exhibit symptoms very similar to the orbit failures and culminated in the amplifier's actually shutting itself off. Another two were characterized by small dips in RF output at specific temperatures. No other symptom of anomalous behavior was observed at the time of the RF dips. The final two were "minor" transients in helix current observed during the first 3 to 4 days of the test. These transients did not reappear during the remainder of the testing.

10.1 ANALYSIS OF RF OUTPUT ANOMALIES (TWTA S/N 14-24 AND 14-25)

During the 400-hour extended T/V tests, units 14-24 and 14-25 displayed periodic dips in RF output power. These dips were regular and appeared at the same point in each temperature cycle. Subsequent diagnostic testing demonstrated that both amplifiers had TWT input connections sensitive to mechanical pressure and temperature transitions. Removal of the TWT connector and inspection revealed:

a) 14-24 - The TWT input match pipe, which is the concentric part surrounding the conductive pin fastened to the helix wire, was off center in its alignment with the TWT input connector.

b) 14-25 - The same as above with an additional problem that a build-up of braze material had occurred at the base of the center pin in the input match pipe, causing a misfit between the center pin and TWT connector.

The first problem, nonconcentricity, resulted in a strain on the window when the connector was mounted, plus a splaying of both the center and outer spring fingers.

The TWT input connectors were modified by enlarging the mounting holes from 0.100-inch diameter to 0.130-inch to allow the connector to seat itself properly over the match pipe. Also, both the connector center pin and outer fingers were replaced.

The input connector on S/N 14-25 was also raised with 0.030-inch shims to prevent the fingers from reaching the braze fillet.

The units were retested on a thermal plate and found to be insensitive to mechanical pressure and temperature transitions.

10.2 ANALYSIS OF AMPLIFIER SHUTDOWN (S/N 14-15 AND S/N 24-26)

During the initial testing, while at atmospheric pressure and temperature cycling to check the chamber thermal-control equipment, S/N 14-15 shut itself off twice. As there was no prior warning and the test cables were not fully secured, it was assumed to be a loose connection or similar problem and the test continued.

After evacuation of the chamber, the data was normal for the first 48 hours. After 48 hours, spikes began appearing on helix current telemetry which built up in amplitude and number of occurrences for the next 36 to 48 hours and then decreased again. After another period of about 24 hours of normal data, the unit tripped off.

The unit was commanded back ON and operated until 18 June 1977, when it again tripped off. On 20 June 1977, it appeared to re-command itself ON, but it seems more likely that this was unknowingly caused by the operator since he was handling the test equipment at the time of the event.

On 21 June 1977, it again tripped off, and attempts to restart it on June 22 were unsuccessful. The unit would time out normally and trip at high voltage turn-on. The unit was removed from the chamber and results confirmed on the test bench. Through a series of tests, the problem was isolated to the TWT, which was removed and rerouted for further analysis.

The power supply was evaluated in a thermal chamber and performed in a normal manner.

The TWT (265HB, S/N 450) leads were separated from the power supply (TWTA S/N 14-15) and it was found to have a 38,000-ohm path between collector and ground. Prior to disassembly, the flatness of the baseplate of the TWT was measured and found to have an 0.0045-inch deformation across the collector portion of the baseplate. The collector region of the tube was then x-rayed with no visual defects noted.

The input and output connectors were removed. The ohmmeter was connected between the collector lead and the baseplate while the collector lead was severed. The ohmmeter reading changed from 38,000 ohms to infinity, confirming a short between the collector and baseplate. The ohmmeter

was then connected between the collector and the baseplate and still indicated a reading of 38,000 ohms. It was connected and left for the balance of the analysis.

Potting was then carefully removed from the area around the collector to baseplate region, exposing the BeO ceramic insulator which conducts the heat of the collector to the baseplate while acting to insulate the collector from the baseplate (ground).

Under the barrel/collector extension, a small region was found where the conformal coating had torn away from the BeO insulator but adhered to potting. With movement of this piece, the ohmmeter varied from 38,000 ohms to 1 megohm, where it remained after release of this portion. The section was removed for analysis.

A dark line was found on the insulator which was thought to be the carbon path of an arc between collector and baseplate. This line was subsequently removed by soaking a cellulose acetate strip in acetone and holding on the area for a few minutes before releasing the acetate strip. Three such transfers were made for subsequent analysis.

In contrast to S/N 14-15 where a specific failure was discovered and identified, the failure investigation of S/N 24-26 has been frustrating in its elusiveness and nonrepeatability.

HLTWTA SN 24-26 was subjected to rigorous testing, including temperature cycling and vacuum testing, during the period 25 June 1977 to 13 July 1977. Erratic behavior of the heater voltage telemetry occurred and infrequent large transients were noted on the helix current during the course of testing. Also, on one occasion when the temperature reached 140^{o}F, the unit turned off.

Following the above testing, the unit was placed in storage for approximately three weeks. After which time, it was again tested in the thermal vacuum chamber. After a brief period of operation, the amplifier shut itself off, apparently due to helix overcurrent.

Subsequently, the unit successfully passed two hi-pot tests of 4 hours each. Further testing isolated the problem to insufficient spacing which caused arcing between a high-voltage wire and the telemetry board above it. Replacement of the defective items was effected and the unit proceeded through final testing.

During the final functional test, prior to shipping, a cathode activity time-to-knee (TTK) of 14.2 seconds was measured. The minimum acceptable value for this measurement is 15 seconds.

Concern was expressed over the downward trend of this parameter. Therefore, to ensure the stability of the tube, it was tested at ambient temperature and pressure with a small signal drive for 100 hours.

TTK readings after this stabilization burn-in measured 14.5 and 14.6 seconds. It was therefore concluded that the prior reading of 14.2 seconds was a random variation and the HLTWTA is flightworthy.

10.3 HELIX CURRENT TRANSIENTS (S/N 14-21 AND 24-19)

Two TWTAs, S/N 14-21 and 24-19 displayed helix current spikes early in the 18-day temperature cycling vacuum test. These spikes disappeared after 3 or 4 days of testing and never repeated. They were never of sufficient amplitude to initiate shutdown of the amplifiers.

It was noted at the time by the vendor that this type of anomaly was not at all unusual the first time a TWT was exposed to a new environment never seen before. At present these units will be hi-pot tested. If the test does not produce any failures, they will undergo an additional 100 hours of temperature cycling vacuum testing. At this time, assuming no failures, they will be given consideration as flightworthy TWTAs.

11. RECOMMENDATIONS

11. RECOMMENDATIONS

Measures must be taken to guard against a recurrence of the 9438 failure. In the course of this investigation, several actions were considered. These included both TWTA and satellite design changes, as well as process and testing improvements. Consideration of what changes and improvements should be selected is influenced by factors involving the present status of the remaining amplifiers and satellites scheduled for launch as part of the DSCS-II program. Specific factors of this nature include the following:

- All the HLTWTAs for F8 through F12 had completed manufacturing and most had completed acceptance test.
- A new traveling wave tube requires 2000 hours of burn-in before it can be assembled with a power supply into a TWTA. Five hundred hours of burn-in are then required on the amplifiers before installation on a satellite.
- DSCS-II satellites F13 through F16 will not use this model amplifier. A new 40-watt TWTA of a different design is planned for use on these satellites.

The existence of the above factors cannot be ignored in the final selection of design, processing, and test changes to be implemented for the amplifiers on F9 through F12. However, they were not used to constrain initial consideration of any possible actions which could be taken to enhance the reliability of the amplifiers used on F9 through F12.

During this investigation, it became apparent that the 40-watt TWTA, presently being procured from the same vendor, used a number of design concepts, materials, and processes common to the 20-watt TWTA installed in satellites F1 through F12. A specific review was performed of this new amplifier by members of the investigation team and recommendations formulated for improving its design and manufacture. These are summarized later in this section.

11.1 DESIGN CHANGES

The design changes can be grouped into two classes; those involving satellite changes, and those representing amplifier changes. The one

change in the first category involves a redesign of the satellite mounting configuration for the HLTWTA. Those in the second category include:

a) Redesign of the TWT collector encapsulation system

b) Redesign of the TWT collector assembly to increase the surface length of the insulator used under the collector

c) Modification of the TWT power supply to allow disabling of the helix overcurrent sense circuit prior to launch

d) Redesign of the TWT collector assembly to locate the collector insulators inside the vacuum container.

Each of these recommendations has been studied and is briefly discussed below.

11.1.1 Satellite Mounting

The thermal and mechanical stress analysis performed during this investigation showed that the present satellite mounting configuration using three 0.005-inch thick indium gaskets under the TWT collector did introduce some mechanical stresses into the collector assembly. A series of thermal evaluation tests indicated this stacked configuration was not necessary to maintain acceptable cooling of the TWT. A single gasket would suffice. Use of a single gasket provides a flatter mounting surface and lowers the mechanical stresses. When installing the TWTA on the satellite, four screws are removed from the amplifier baseplate and four new screws inserted through the thermal fin into the TWTA. During this exchange, the collector end of the TWT is not positively attached to the amplifier baseplate. The interface between the TWT and the amplifier baseplate uses an indium gasket for improved surface contact. This type of interface is pressure sensitive and some relief of pressure would occur when these screws are removed. Leaving one of these screws in place when installing the TWTA on the satellite would maintain the pressure at the TWT/amplifier interface. The three remaining screws still provide adequate mounting strength for the amplifier.

It is recommended that only one indium gasket be used at the interface between the satellite and the amplifier and that one of the TWT installation screws in the amplifier be left in place when the unit is installed on the satellite.

11.1.2 TWT Collector Encapsulation System

One of the least understood portions of the TWT was the high-voltage encapsulation system for the collector. Although considerable experience has been gained by the vendor in the use of this system, little analytical or empirical data was available to evaluate stress margins, cleanliness requirements, rework risk, etc. Some short-term strength and rework tests were run as part of this investigation, but they could produce only very preliminary qualitative data. The conclusion reached by the investigation team was that the potting system was adequate if it was processed perfectly. However, the system could not tolerate any imperfections in process such as cleaning, improper storage, etc.

The types of changes which were considered as improving the encapsulation system include:

a) Select a new conformal coating material and/or encapsulant which has more bond strength.

b) Revise the collector assembly configuration to provide stress relief of the encapsulant during thermal cycles.

c) Revise the configuration of the collector assembly to allow better access to all surfaces of the collector, beryllium oxide insulator, and mounting assembly for cleaning prior to conformal coating.

It is recognized that considerable development would be required before a new potting system could be incorporated to a flight TWTA. It is certain this could not be accomplished for F9 through F12 and maintain even an approximation of the existing launch schedule. However, incorporation of these design concepts into future DSCS-II TWTAs is highly recommended.

11.1.3 Increased Path Length at Collector Insulator

The present collector insulator contains no provisions for lengthening the surface path length across which an arc must develop to create a high-voltage breakdown. Also, the mating surfaces to which the insulator is soldered have sharp edges and corners on all sides. Additional margin could be designed into the collector assembly if the insulator surface were reshaped to increase its length and the mounting surfaces configured with rounded edges. An increase in path length by a factor of two would be desirable.

Incorporation of this type of design change into the 20-watt TWTs would require complete disassembly of the TWT from its baseplate, a process involving removing the encapsulant and unsoldering the collector assembly. The alternative is to build new TWTs. In either case, the time required for such an activity is grossly inconsistent with the F9 through F12 schedule. However, it is strongly recommended that these types of design concepts be incorporated in future DSCS-II TWTs.

11.1.4 Helix Overcurrent Trip Circuit

Although it was not considered likely, the investigation team could not totally rule out the helix overcurrent sense circuit as the cause of on-orbit failures. On the remote chance that a malfunction of this circuit was actually the cause of one or more orbit failures, it would seem desirable that provisions be incorporated into the TWTA to disable this circuit prior to launch. The circuit should be kept operational during ground test, particularly since it is used to terminate the cathode activity test. Disabling this circuit has a disadvantage in that any helix overcurrent load created by the TWTA must now be supplied by the power supply until the primary bus input current has increased to greater than 9 amperes. However, if it is assumed that the helix overcurrent is caused by a permanent abnormality in the TWT or its power supply, then this consideration is of no consequence.

On balance, this investigation concludes that it is recommended the helix overcurrent shutoff function be disabled prior to launch.

11.1.5 TWT Collector Assembly Redesign

A technique used in some TWT designs is to include the collector insulators within the vacuum enclosure containing the collector. The exterior of the vacuum enclosure is at ground potential and can be mounted onto the TWT baseplate without concern for high-voltage isolation. Once the vacuum has been successfully established within the TWT, there is no longer any need to be concerned about bonding of conformal coating or encapsulants since none are used where there is any requirement to stand off a high voltage.

This type of major TWT redesign is totally incompatible with any practical schedule for F8 through F12. However, it seems to offer potential advantages in that it can eliminate a critical part of the TWT design which has proven difficult to implement into quality hardware. Hence, it is recommended that careful consideration be given to this type of design for future DSCS-II HLTWTA developments.

11.2 PROCESS AND TESTING CHANGES

The serious schedule impact of any significant TWT design changes and the existence of an inventory of eighteen completed amplifiers for F9 through F12 make it imperative that the investigation team consider possible test and screening methods for selecting TWTAs from inventory for use on flight satellites. Three such activities were considered for this purpose:

a) Perform an extended temperature cycling vacuum test on each TWTA before installation on a satellite.

b) Perform an improved hi-pot test on each TWT after the extended thermal vacuum test to show positive margin between the high voltage standoff capability of each TWT and its operating voltages.

c) Obtain continuous recordings of TWTA telemetry measurements during unit and system vacuum testing to check for transient perturbations which may not show in the sampled data telemetry system.

Some conclusions on each of these recommendations are briefly discussed in subsequent paragraphs.

11.2.1 Extended Temperature Cycling Vacuum Test

The early timing of the F8 orbit failure suggested that it could have been avoided if the TWTAs had been exposed to a longer thermal vacuum test prior to launch. Also, it was reported from other satellite programs with successful orbit TWT experience that they exposed their TWTAs to up to 30 days of thermal vacuum testing before launch. With these considerations in mind, it was recommended that the HLTWTAs in inventory be subjected to a 30-day temperature-cycling vacuum test. As reported in Section 8 of this report, this recommendation was adopted and the test program initiated.

Subsequent to initiation of the test program, it was shortened to 18 days. Shortening the test seemed reasonable based on the fact that all anomalous performance became evident in the first 4 to 7 days, while the latter portions of the test seemed to be serving mainly to ensure proper operation or as a period to verify any anomalous operation shown early in the testing. It is strongly recommended that this type of extended vacuum test be performed on all future DSCS-II HLTWTAs.

11.2.2 High Potential* Testing

Near completion of manufacturing, each TWT is subjected to a short high-potential test at 1.5 times rated operating voltage. This is done to screen out any TWTs which are not properly potted and might fail in future testing. The high-potential test is performed at higher than operating voltages and indicates a failure at discharge levels lower than an actual arc discharge. Hence, it should be able to screen out TWTs which have latent defects in the encapsulation system and would fail early in life.

The optimum high-potential test, defined in terms of applied voltage and discharge levels which indicate a failure, will require some study. The applied voltage should not be so high that it will induce degradation in the encapsulant, conformal coat, or insulators. It should be sufficiently above the operating voltage that it will establish some margin of safety. Similarly, the discharge energy trip point of the test should be low enough to detect less than critical flaws in the TWT, but not so low that it trips on its own corona or from microdischarges in the TWT which do not indicate life shortening flaws.

It was felt by the investigative team that a practical high-potential test could be designed for the TWTs in inventory. Also, the amount of rework required on the TWTA to allow performing high-potential test on the TWT is minor and of minimal risk. Therefore, it is strongly recommended such a test be performed on all HLTWTAs used on DSCS-II satellites.

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*High voltage.

11.2.3 Continuous Data Recording

Much of the TWTA telemetry measurements data available to the investigative team was static data, for example, single-value notations of telemetry measurements taken at specific times.

Sampled data from the satellite telemetry system was only available in graphic form after special plotting was performed either by hand or computer. There was no analog recorded data of any TWTAs, either on orbit or in inventory. The investigative group believes that analog recordings of TWTA telemetry measurements and RF performance would be very useful in early detection of latent failures. Hence, it is strongly recommended such data be obtained for future DSCS-II TWTAs. In particular, continuous data should be recorded during the extended temperature cycling vacuum test, during amplifier turn-on in satellite thermal vacuum tests, and during temperature transitions in satellite thermal vacuum tests.

11.2.4 Process and Quality Control

Investigations, plus analyses to date on hardware, have demonstrated that the materials used in TWTA construction are acceptable and adequate for the TRW application and workmanship and quality control are satisfactory. Adhesion is marginal and under high stress is not maintained. To ensure adequate process behavior, the consultant team has made recommendations, implemented by EDD, toward improving the cleanliness and general practices used in the processes--such as the elimination of silicones from the work area and thorough cleaning of the encapsulant curing oven. Investigations are continuing toward implementation of pressure curing the encapsulant and adding fluorescent tracers to the conformal coating to enhance the inspection of its coverage. In the future, activities of this team will be directed toward finding materials with improvements in characteristics and less sensitivity to processing variables.

11.3 ON-ORBIT OPERATIONS

In light of the 9438 failure, the failures observed in the extended thermal-vacuum test, and certain experience reported on other programs, the

investigative group formulated certain recommendations involving orbit operations on future DSCS-II satellites. These can be summarized as follows:

a) Do not turn on the HLTWTAs until a minimum of 14 days after launch. This applies even if the THA fails.

b) If a HLTWTA fails in orbit, the ON command for that unit should be sent to establish that the problem is not a command anomaly. If there is no response, the redundant unit should be commanded ON.

c) Do not turn on the redundant TWTAs during post-launch testing. Turn them on only when required by a failure of a primary TWTA.

The rationale for the steps of this procedure in each case is to seek the minimum risk consistent with supplying the most reliable service to the user. The initial turn-on delay is desirable to conservatively allow for outgassing of newly launched units. The 14-day period was chosen to exceed the one known infant mortality time-to-failure experienced on 9438 and also the times for observed anomalies to clear up on other programs.

If a TWTA heater assembly (THA) should fail at any time prior to HLTWTA turn-on, the TWTAs associated with the failed THA could get as cold as $14^{\circ}F$ worst case. The recommendation not to turn on the HLTWTA in this situation is based on the following:

a) If the THA failure occurs at initial turn-on, 7 to 8 hours of outgassing time is not sufficient to ensure outgassing of the TWTA.

b) All TWTs have been exposed, after encapsulation, to a low-temperature cycle of $-30^{\circ}F$ successfully.

c) All other components on the despun platform will not cool below their low-temperature turn-on point with a failed THA.

Since switching electronic units on and off always entails some risk of failure (either in the unit or in the command circuit), the minimum risk situation appears to be to leave the redundant units off until needed. Immediate switching to the redundant unit (after checking for a possible command anomaly), rather than attempting to restart a failed unit, may allow the fault to be cleared by further outgassing, thereby preserving the affected unit for future service.

11.4 40-WATT TWTA FOR F13 THROUGH F16

During the course of the investigation, considerable insight was gained into the problems inherent in successfully designing and building a flight-quality TWTA. Currently a new 40-watt TWTA is being developed for use in F13 through F16 DSCS-II satellites. An investigation was conducted to determine the physical construction of this new TWTA. The investigative team was able to formulate a series of concerns and recommendations. First the concerns:

a) The 40-watt amplifier uses the same encapsulation material and technique as used on the 20-watt TWTA. The true capability of this potting system never became known to the investigative group. Hence, there is a real concern that this system will be functional for the 40-watt amplifiers.

b) Very few data were available to define the stability margin of the TWT power supply when operated with a dynamic load such as a TWT. Lack of such data leaves the investigative group with a concern that this stability may be marginal and that unstable operation could be possible under certain operating conditions with certain dynamic load characteristics.

The recommendations for corrective action arising from these concerns and the investigations of both the 20- and 40-watt TWTAs can be summarized as follows:

a) The collector should be redesigned. The recommended design is one in which the thermally stressed insulating ceramics are placed inside the vacuum envelope so that there is no question that the combination of high voltage and high temperature can lead to failure of the potting system. The high-voltage insulator used to bring voltage into the collector should be designed to safely stand off the collector voltage without the aid of conformal coating and potting. An alternative design is one based upon the design used in the 20-watt TWT but with a much thicker BeO slab insulator designed for long creepage paths.

b) The electron gun body should be redesigned so that the anode insulator is longer or has a longer creepage path, consistent with good design practice for an insulator holding off 3600 volts.

c) Criteria for high-voltage design and packaging should be established and implemented for both the TWT and the power supply. As a minimum, these criteria should include:

   1) Reduction of the occurrence of sharp edges in accordance with good engineering practice for reduction of electrostatic stress.

   2) Determination of working dc voltages across insulation and test to at least 200 percent of these working voltage levels.

   3) Mechanically packaging to guarantee spacing of all high-voltage dielectrics and leads.

d) Conduct a complete stability analysis including loop frequency/gain plots and phase margin with the TWT as a load. Parameters used in the analysis should include, but not be limited to, the variation of helix current as a function of cathode-to-helix voltage under the following conditions:

   1) Acceptance temperature range

   2) RF drive levels from small signal to specified overdrive level

   3) Simulated end-of-life for the TWT (perhaps by reducing heater voltage)

   4) Cathode voltages to include the normal regulation range

   5) Cathode voltages in the region of the helix peak

e) The package should be designed for venting, and the outgassing of materials should be identified. Specifications defining the pressure conditions the TWTA is designed for should be generated.

f) A program for burn-in of TWTAs in a vacuum environment with power and temperature cycling should be established.

12. HIGH POTENTIAL TESTING

12. HIGH-POTENTIAL TESTING

As a direct result of the recommendations described in Section 11.2.2, all HLTWTAs were subjected to additional high-potential testing, as described below:

a) Perform a limited baseline functional test on the TWTA.

b) Electrically demate the TWT.

c) Perform a 4-hour high-potential test.

d) If test is successful, reintegrate TWT and EPC.

e) Perform a one-axis nonoperating vibration test.

f) Perform a 24-hour thermal-vacuum test with four temperature cycles to acceptance test limits.

g) Perform a limited final functional test on TWTA.

Some units were tested to an earlier test plan which included a 24-hour thermal stress test involving four temperature cycles from +60° to +146°F, up to 14 hours high-potential test, and longer thermal-vacuum tests. See Table 12.1-1 for test data on all HLTWTAs.

High-potential tests were performed on all units in October 1977. Results indicated four confirmed failures: S/Ns 14-19, 14-21, 24-20, and 24-19. These four TWTs were reworked and retested as follows:

a) Perform high-potential test on non-failed end of TWT.

b) Demate EPC and TWT mechanically.

c) Check flatness of TWT base and TWTA chassis (inside and outside).

d) Remove all potting from affected end of TWT (replace ceramic insulators as required).

e) Reassemble per normal "final package assembly" procedure (except using two-layer conformal coat), including vacuum/high-potential tests and temperature cycling from -50° to +170°F.

Table 12.1-1. HLTWTA Special Testing Summary

Unit S/N	No. of Hi-Pots	Hi-Pots Hours	Failure	Remarks	Date Returned to TRW
14-25	1	4	None		10/22/77
14-26	1	4	None		10/22/77
24-23	1	4	None		10/22/77
24-25	1	4	None		10/22/77
14-20	2	10/4	None		10/24/77
14-23	2	10/4	None		10/24/77
24-22	1	10	None		10/26/77
24-24	1	4	None		10/26/77
14-22	1	4	None		10/26/77
14-24	3	14/14/7	None		11/10/77
24-27	2	10/4	None		02/06/78
24-21	2	10/4	None		12/09/77
14-15 (450)	1 Prod. 1	1 8	Broken wire in High voltage unit	All failed units, after rework, went through the following test cycle:	03/13/78
24-26	2	4/4	Power Supply short	Limited Functional Vibration	04/05/78
14-19	4	4/2/1/1	Collector Failed	Thermal Vacuum (100 hrs)	02/23/78
14-21	4	4/2/1/1	Collector Failed	Limited Functional	02/22/78
24-20	4	4/2/1/1	Collector Failed		02/22/78
24-19*	4	13/14/1	Cathode Failed	Hi-pot tests were conducted after rework, except for SN 24-26.	03/21/78

NOTE: All tubes were subjected to a 400-hour thermal vacuum test. Only one, SN 14-15, failed this test.

*Tube assembly replaced in this unit during rework

Two units (S/Ns 14-24 and 24-27) encountered a single trip during the high-potential tests. The tests were repeated a number of times and no repetition of the trip occurred. These tubes have, in effect, more than passed the high-potential confirmation test. As a result, they are considered flightworthy and completed the test program which included 100 hours in thermal vacuum at four temperature cycles per day.